Open-orbit microwave transmission peaks in copper*

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We report strong sharp peaks of microwave transmission through single-crystal copper plates at cryogenic temperatures for particular orientations of the applied dc magnetic field. We associate these orientations with open orbits. While we have no explanation for the transport mechanism, we show that the energy cannot be carried ballistically.

We report our observation of intense sharp peaks of microwave energy transmitted through single-crystal plates of high-purity copper at cryogenic temperatures for particular orientations of the applied dc magnetic field. We have correlated the special orientations of the magnetic field for which transmission peaks occur with those which are known to allow open orbits.[1] In an effort to clarify the mode of energy propagation we have performed masking experiments which would seem to rule out direct ballistic transport by electrons. Examples of the data are provided which illustrate the characteristic features of this new electromagnetic transport mode.

Our measurements are made utilizing the microwave transmission technique (MTT) wherein the sample forms the common wall between two cavities tuned to the same frequency. In MTT power is incident into one cavity, and that power which has been transmitted through the sample and reradiated into the second cavity is detected as a function of applied variables such as the dc magnetic field.[2] In the present experiments the samples consisted of oriented single-crystal copper slices, 0.01 to 0.05 cm thick, cut from boules whose resistivity ratio, room temperature to 4.2 K, varied between 10 000 and 25 000. Typical conditions are: incident power, 10 mW; frequency, 9.2 GHz; temperature, 1.4 to 20 K; dc field, 10 to 20 kG. The detector sensitivity is $\approx 10^{-19}$ W at 3-Hz bandwidth, and the peak transmitted power $\approx 10^{-14}$ W. The dc field may be oriented anywhere in the plane containing the normal to the sample, and is always perpendicular to the rf magnetic field. The magnet is equipped with a motor-driven precision angular readout so that the transmitted power (or field) may be measured as a function of orientation of the dc magnetic field to the sample surface at fixed magnitude.[3]

There are two general modes of electromagnetic energy transport through the sample: (i) energy is carried across by an electromagnetic wave when circumstances result such that regions of the appropriate dispersion relations have sufficiently undamped wavevector, or, (ii) the energy is transmitted ballistically, that is, carried by those electrons which are excited within the narrow skin depth on one surface and then manage to travel unimpeded across the sample and radiate coherently on the far side. An example of the first mechanism is transmission electron spin resonance,[2] whereas the Gantmakher size effect is an example of the second.[4] There are a surprisingly large number of microwave energy transport modes in high-purity metals at cryogenic temperatures. In simple metals, with spherical Fermi surfaces, most are at least qualitatively, and often even quantitatively, understood. In a metal like copper, the behavior of the transmitted power as a function of the magnitude and orientation of an applied dc field is often quite complex, in general representing the superposition of several modes. However, under certain experimental conditions, a given mode of transmission can be sufficiently dominant so that it may be studied in appropriate detail as relevant experimental parameters are varied. When working with relatively thick samples, we find that for certain orientations of magnetic field with respect to the crystallographic axes, there are very sharp peaks of transmitted energy which completely dominate over all other signals. We identify these peaks as next described.

Our apparatus has provisions for combining the transmitted field H_{rf}, emanating from the second cavity with a much larger reference field H_{REF}, which originates from the main oscillator. The detected signal in this case is proportional to only the component of the transmitted field in phase with the reference, or $\propto \vec{H}_{rf} \cdot \vec{H}_{REF}$. Alternatively, we may also arrange to measure the modulus of $\vec{H}_{rf}$ by rotating the phase of the reference field continuously through multiples of 2π at a rate fast compared with either the phase or amplitude variations of $\vec{H}_{rf}$. The envelope of the rectified output under the conditions then corresponds to the $|\vec{H}_{rf}|$.

In Fig. 1(a) we present a signal proportional to $\vec{H}_{rf} \cdot \vec{H}_{REF}$ as a function of the angular orientation of an applied dc magnetic field. In Fig. 1(b) we

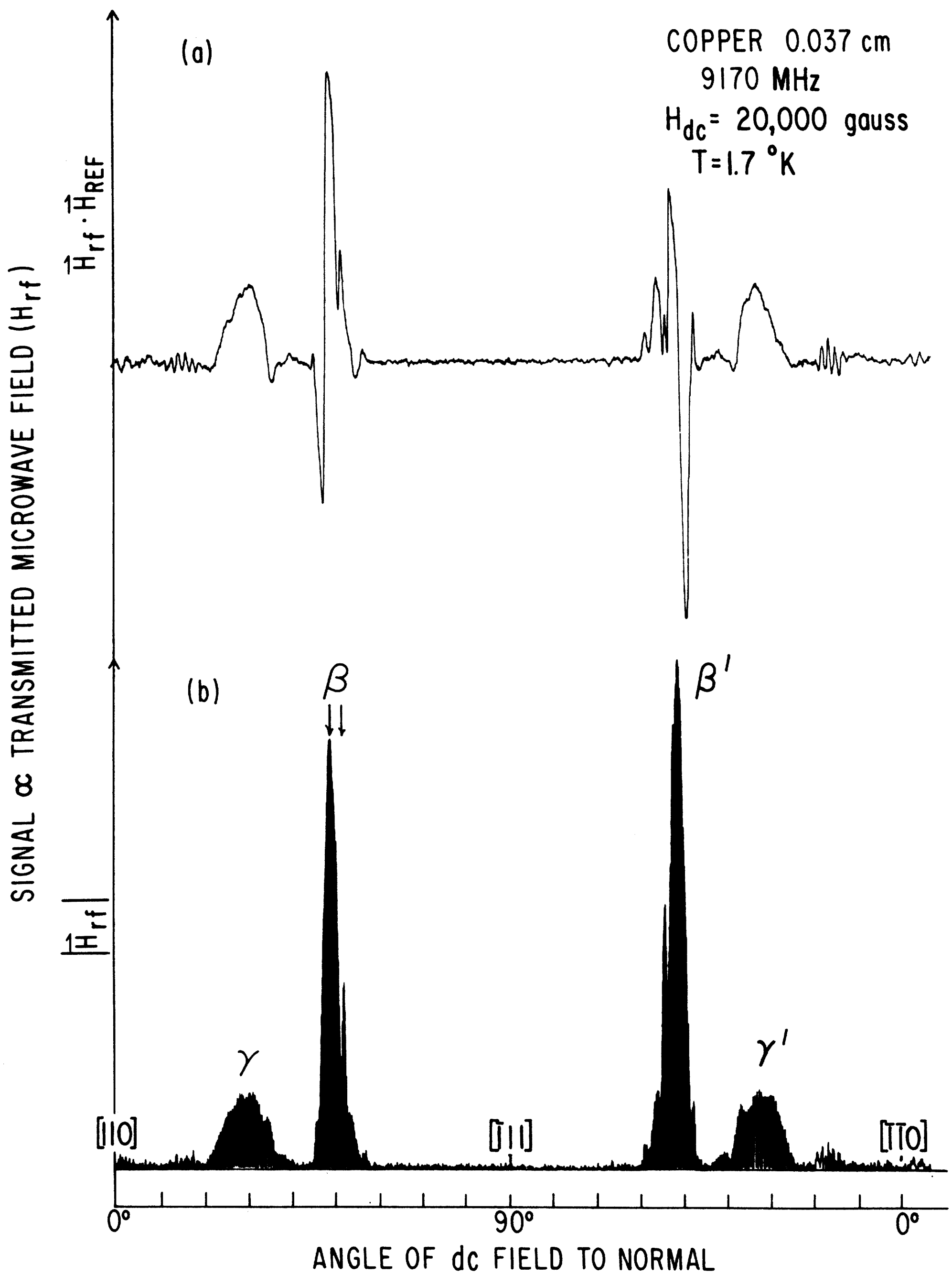

FIG. 1. Typical transmitted microwave field signals as a function of the angle of the dc magnetic field to the sample normal. The crystallographic axes are as indicated. (a) Transmitted field projected onto a constant reference field. The apparent asymmetry of the signals is due to a slight misorientation of the crystal axis. (b) Magnitude of the transmitted microwave field. The two peaks labeled β and γ are identified with open orbits as shown in Fig. 3. Note the fine structure of the β peak indicated by the arrows, which are further resolved in Fig. 2. The power at the β peak is over 10^4 times that in the vicinity of 90°.

present the corresponding modulus signal $|\vec{H}_{rf}|$. Two major peaks occur at the angles indicated as β and γ. These peaks are quite striking. The ratio of the power transmitted at the β peak, to that of the base line is over four orders of magnitude, and as indicated by the double arrows, there is a fine structure. In Fig. 2 we present $|\vec{H}_{rf}|$ at one of the β peaks with increased resolution. We can

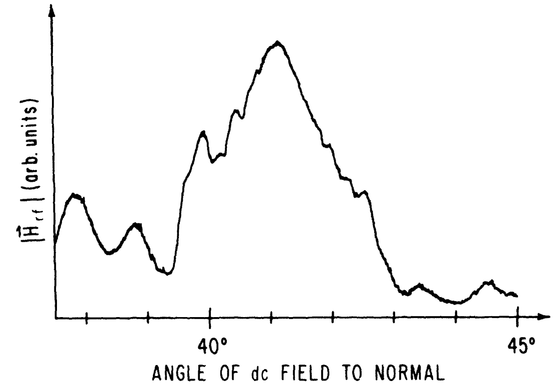

FIG. 2. Magnitude of the transmitted microwave field in the vicinity of the β peak of Fig. 1. The dc magnetic field was 18 kG and the temperature 1.4 K.

see there is a rich spectrum over a region of only a few degrees. The primary features of the spectrum repeat from sample to sample, although we do not know the limiting resolution as our orientation accuracy was typically ±1°.

In Fig. 3 we present a sector of a stereographic projection with cubic symmetry. The known open-orbit directions for copper are as indicated.[5] We note that for the locus of magnetic field sweep of Fig. 1, peaks would be predicted at the three angles labeled α, β, and γ. The predicted locations agree very well with the β and γ peaks observed. An additional peak corresponding to α is observed for a thinner (0.01 cm) sample. We have taken data for other sample orientations. For the trajectory indicated by the crossings a-f in Fig. 3, we found strong peaks at b and d. When the field locus is such that it is always perpendicular to an open orbit, for example [110]→[100], we find a complicated structure with some sharp peaks at intermediate angles.

We do not understand the widths or amplitudes of the observed peaks such as those in Fig. 1, although it seems clear they are related to open orbits. We find the linewidths are independent of temperature, which suggests that they are determined by properties of the Fermi surface and the orientation. The signal amplitude decreases with temperature such that the log of the signal is proportional to the temperature-dependent resistivity. The power transmitted at the peaks decreases with increasing sample thickness. No detailed quantitative comparison between the transmittance of different samples was made, for the intensity at the peaks was sensitive to accidental mechanical damage suffered by the specimens during preparation and mounting. At fields below 10 kG it is difficult to identify the open-orbit peaks due to structure from other modes. For any given peak we find a monotonic increase in amplitude from 10 to 20 kG.

In order to determine if the energy was being carried ballistically, by electrons streaming along open orbits, we performed the following experiment. Consider the sample pertaining to the data of Fig. 1. The dc magnetic field rotates in a horizontal plane containing the normal to the crystal which was the [110]. The vertical is along the sample [1$\bar{1}$2]. Referring to Fig. 3, the crossing at β corresponds to a [100] open orbit, and at β' to the [010] case. The projection of the trajectory of electrons on the vertical plane containing the normal to the sample would make an angle to the vertical as shown in Fig. 4(a). As is evident from Fig. 4(b), if masks were placed within the cavity

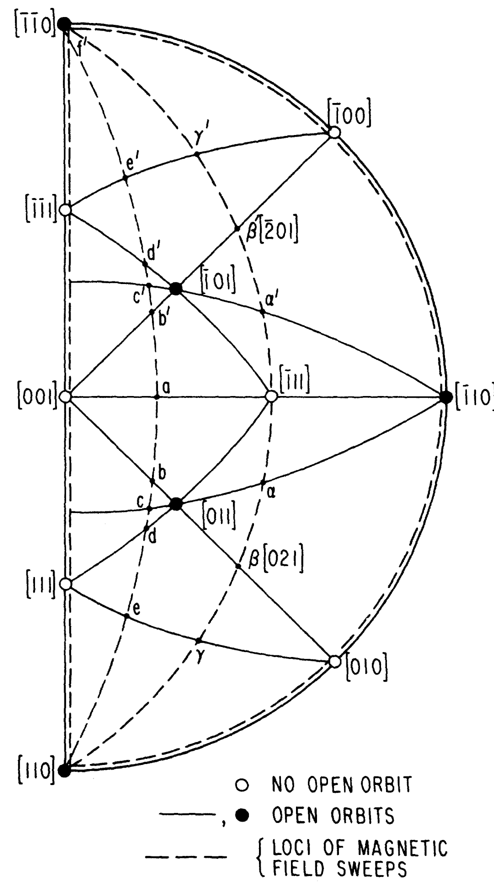

FIG. 3. Stereographic projection showing the loci of the magnetic field studied in our experiments, and those field directions which give rise to primary and secondary open orbits (Ref. 1). The intersections labeled α to γ, and a to f (and the corresponding directions, marked by a dash) represent orientations where power peaks might be expected. As discussed in the text, strong peaks were observed at β, γ, and at b and d (and their corresponding directions).

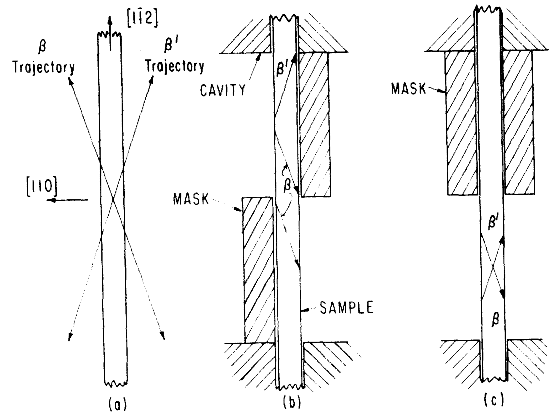

FIG. 4. Pictorial representation of electron open-orbit trajectories for the situation pertaining to the masking tests discussed in the text. The figures are drawn to scale. (a) A view of the sample parallel to the surface. For the orientations indicated, when the magnetic field is at the angle corresponding to the β peak of Fig. 1 (and Fig. 3) the projection of the open-orbit electron trajectory is approximately 19° from the vertical as shown. (b) The sample lies between two cavities, and is asymmetrically masked by pieces of brass shim. As can be seen, the β orientation trajectories could still communicate between the two cavities, whereas the β' trajectory could not. (c) The sample lies between two cavities and is now symmetrically masked by brass shims. The β and β' trajectories are symmetrical with respect to the masking geometry, but there is a relatively unobstructed path along these trajectories from one cavity to the other.

on each side of the sample as shown, and the energy was carried ballistically, one would expect only a slight diminution in overall signal for the β field orientation, compared to a drastic decrease for β'. The results are shown in Fig. 5 for an orientation of the [1$\bar{1}$2] inadvertantly rotated from the vertical by 6.8°. Despite this complication, we still expect a significant asymmetry in signal amplitudes with the masks in place. Because of the greatly reduced amplitudes [about 30 dB down with respect to configuration of Fig. 4(a)], it was impractical to take modulus data, and we present the $\vec{H}_{rf} \cdot \vec{H}_{REF}$ signal as a function of dc orientation. We note that within the noise there is certainly no marked amplitude asymmetry. This experiment would thus appear to rule out the ballistic transport mechanism and to suggest an electromagnetic

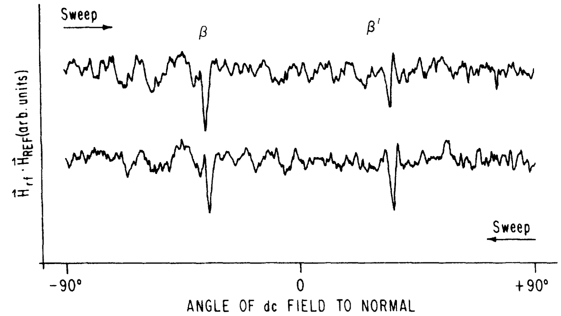

FIG. 5. Transmitted field projected upon a constant reference as a function of the orientation of the dc magnetic field to the sample surface under orientation and masking conditions of Fig. 4(b). The peaks correspond to that labeled β and β' in Fig. 1, and as can be seen are basically symmetric in amplitude. The dc magnetic field was 18 kG, temperature 1.4 K, and sample thickness 0.055 cm.

wave mode.

As a further check, using the same sample, we arranged the masks as in Fig. 4(c). We found that the transmitted power for this case was approximately 30 dB larger when compared to the configuration of Fig. 4(b). This result again is consistent with a nonballistic mechanism.

The effects of open orbits on other modes of energy transmission, such as helicons, have been reported.[6] The power peaks displayed in Fig. 1 do not appear to be modifications of another transport mode, although this cannot be ruled out. The underlying mode could be too weak to see except when greatly enhanced near the open-orbit locations. In either event, since the power peaks can be as much as four orders of magnitude larger than the baseline, and often with a rich angular structure, we suggest that it may be possible to interpret such data for information concerning details of the Fermi surface, and to ascertain the relaxation times of the particular groups of contributing electrons. However, it would seem that further progress must await the development of some theoretical explanation of this electromagnetic transmission mode.

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[1]E. Fawcett, Adv. Phys. 13, 139–191 (1963); J. R. Klauder and J. E. Kunzler, *Proceedings of the International Conference on Fermi Surface* (Wiley, New York, 1960).
[2]A detailed description of the spectrometer is being prepared. An introduction to the method including illustrations of other applications in metals may be found in S. Schultz, *Measurements of Physical Properties,*

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[3]The motorized magnet rotator was built by D. Eigler, and the high-resolution angular readout by D. Pinkel (unpublished).

[4]E. A. Kaner and V. F. Gantmakher, Usp. Fiz. Nauk 94, 193-241 (1968) [Sov. Phys.-Usp. 11, 81 (1968)]. In particular they refer to the second mechanism for anomalous penetration as due to the trajectory of individual charged quasiparticles. It is in this sense that we use the term ballistic.

[5]We have restricted our analysis in Fig. 3 to only include primary and secondary open orbits.

[6]C. C. Grimes, G. Adams, and P. H. Schmidt, Phys. Rev. Lett. 15, 409 (1965); J. R. Merrill, Phys. Rev. 166, 716 (1968).