### *Behavior of Electrons in Metals Discussed in Canada*

New techniques for the study of Fermi surfaces in metals have opened up a new field of physical metallurgy. The methods, based on investigations of cyclotron resonance, the de Haas–van Alphen effect and the change of surface impedance with magnetic field, have been used with some pure metals and are beginning to be applied to alloys, compounds, semiconductors and semimetals.

A summer school on these and related topics of electrons in metals was held from 21 Aug. to 1 Sept. at Alta Lake, a mountain village 75 miles north of Vancouver, B.C. 40 physicists took part in the lecture and discussion program.

#### *Energy levels in lattice*

Brian Pippard of Cambridge University began with an elegant series of lectures on the behavior of electrons in weak and strong magnetic fields. He treated the problem of a charged particle moving in a periodic lattice potential and, at the same time, subjected to a static magnetic field. At sufficiently small magnetic fields (part of the problem is to decide what is meant by "sufficiently small") the particle behaves classically with an energy–momentum relationship determined by the periodic potential in the absence of the magnetic field. In the opposite case of sufficiently large magnetic fields the forces on the particle arising from the periodic potential are small compared with the Lorentz force; so the particle behaves like a free particle in a magnetic field.

Pippard discussed how the energy levels of a charged particle in a two-dimensional lattice change as the magnetic field is increased from the weak-field limit through intermediate values to the high-field limit. He also discussed the effects of these energy-level changes on the oscillatory part of the susceptibility (de Haas–van Alphen effect) and on the transport properties of the metal. His treatment of spin-orbit interaction is particularly illuminating because it gives a physical picture of the origin of large, effective $g$ values that characterize the spin-splitting energies associated with small pieces of the Fermi surface.

#### *Euclidean wave mechanics?*

Having shown in his first seven lectures how wave mechanics can be worked out using only a straight edge and compass, Pippard devoted his remaining time to the subject of magnetoresistance of metals that contain unequal numbers of holes and electrons. According to conventional theory[1] the resistance of such a metal should become independent of field at large fields when $\omega_c\tau \gg 1$, where $\omega_c$ is the cyclotron frequency of the carriers and $\tau$ is their mean relaxation time. In practice the approach of resistance to saturation as observed in many uncompensated metals (for example, copper, potassium) is much less rapid than is implied by the condition $\omega_c\tau \gg 1$, if $\tau$ is obtained from the dc resistance of the metal. Pippard showed how this delayed-saturation effect can be ascribed to small-angle scattering processes and how we can then learn something about the mechanism of these processes in metals.

#### *Fermi surfaces*

Robert Chambers (Bristol) described what is known about the shapes of Fermi surfaces of simple metals, transition metals and magnetically ordered metals. The Fermi surfaces of most simple metals have been mapped out, and they are well described by band-structure calculations where model potentials ("pseudopotentials") are used to describe the interactions between electrons and lattice.

Less experimental and theoretical progress has been made with transition and magnetically ordered metals. Progress in theory is slow because of complications introduced by unfilled $d$ bands on the one hand and by magnetic ordering on the other. Experimental progress has been retarded by the lack of sufficiently pure materials. Chambers also discussed effective masses, Fermi velocities, many-body effects, scattering processes in metals

**PHYSICISTS AT ALTA LAKE. Front row: D. N. Langenberg, R. G. Chambers, W. Mercouroff, A. B. Pippard, A. V. Gold, W. M. Walsh, R. R. Haering and J. F. Cochran.**

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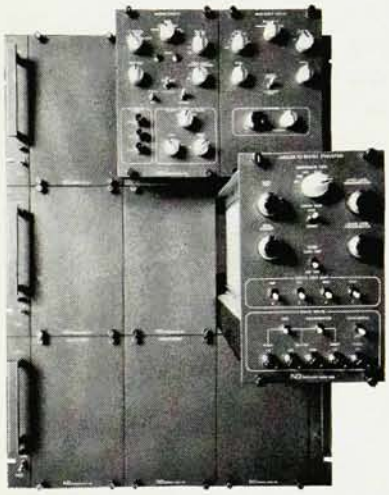

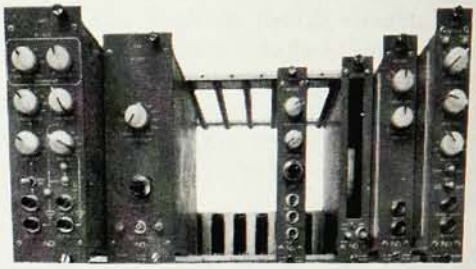

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(including surface scattering), disordered alloys and various methods of investigating the Fermi surface that do not require high purity metals and so are suitable for use with alloys. These latter methods were subdivided according to the use of neutrons, photons, ions or positrons as tools.

### *Surface states*

Frederick Koch (University of Maryland) and D. Llewellyn Williams (University of British Columbia) described recent experiments on cyclotron resonance. Koch has been investigating the *surface states* that are formed when a metal is placed in a magnetic field with the field lines parallel to its surface. The positions and strengths of the resulting peaks in surface impedance are in excellent agreement with a theory of Nee and Prange[2] and can be used to investigate Fermi velocities and the curvature of the Fermi surface along a particular direction in the metal, as well as to obtain an estimate of the fraction of grazing-incidence electrons that are specularly scattered at the metal surface. Williams has been using positron annihilation experiments to map out dimensions of the Fermi surface. He presented results in copper and a copper–zinc alloy that lend weighty support to the thesis that positron annihilation will be the most useful tool for investigations of the Fermi surfaces of disordered alloys.

Chambers's review was complemented by lectures on ordered alloys, compounds, semiconductors and semimetals by Wladimir Mercouroff (Orsay). He described briefly various techniques that have proved useful for the investigation of the Fermi surfaces of these materials and listed the specific substances to which they have been applied. This list was rather short, thus indicating that a whole new field of physical metallurgy is waiting to be explored.

As the two main tools for detailed investigations of the Fermi surfaces of pure metals have been the de Haas–van Alphen effect and surface impedance measurements a series of lectures was devoted to each of these topics. Andrew Gold (Iowa State University) discussed the theory of the de Haas–van Alphen effect, including magnetic interaction effects, magnetic breakdown effects and the effect of many-body interactions. All points were profusely illustrated with appropriate experimental data, much of it from Gold's own laboratory. His lectures concluded with an evaluation of experimental techniques and a list of all the pure metals in which the de Haas–van Alphen effect has been observed.

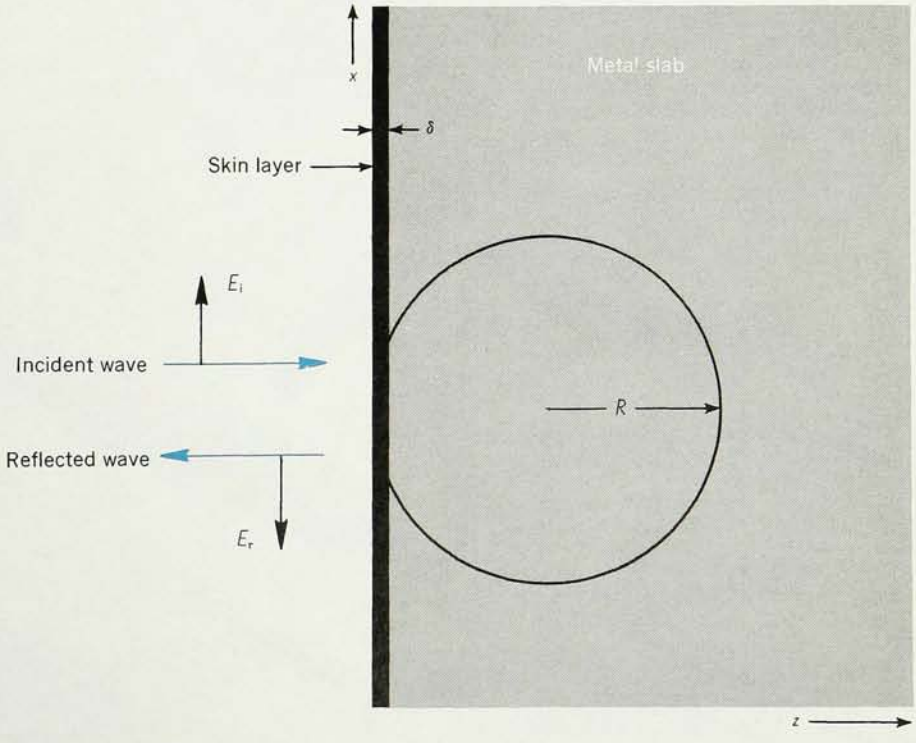
### *Surface impedance variations*

The surface impedance of a metal, $Z = R + iX$, is proportional to the ratio of **E** to **H** just inside the metal surface. Most of the incident wave that falls upon a metal is reflected and the interference between reflected and incident waves results in a very small electric field just inside the metal and a magnetic field with nearly twice the amplitude of that in the incident wave. The alternating fields in the metal are rapidly attenuated toward its interior and are contained largely within a distance $\delta$ of the metal surface, where $\delta \propto |Z|$. The skin depth in very pure metals and at temperatures low enough that $\delta/l \ll 1$ ($l$ is the mean free path of the carriers) is independent of mean free path and varies as $\omega^{-1/3}$, where $\omega$ is the frequency of the radiation. For most metals $\delta \approx 10^{-4}$ cm at 1 MHz. Over the frequency range 0 to $10^{12}$ Hz the surface impedance in zero, static magnetic field does not contain very much detailed information on the behavior of current carriers in the metal, but upon application of a steady magnetic field, $H_0$, the surface impedance displays a rich variety of phenomena that can be used to measure momenta, mean free paths and effective masses of the current carriers in the metal. These variations with magnetic field were discussed by Michael Walsh (Bell Labs) who covered both temporal and spatial resonances.

### *Temporal resonances*

An example of the first is the Azbel'-Kaner cyclotron resonance: A group of carriers in the metal, all with the same cyclotron frequency and hence the same cyclotron mass, return to the surface of the metal in phase with the

**TEMPORAL RESONANCE** or Azbel'-Kaner cyclotron resonance. **A static magnetic field is applied along the $y$ axis. When the cyclotron frequency of a group of carriers, $\omega_c = eH/mc$, is such that $\omega_c = \omega/n$ (where $\omega$ is the frequency of the incident radiation and $n$ is an integer) the carriers pass through the skin layer in phase with the alternating electric field.** —FIG. 1



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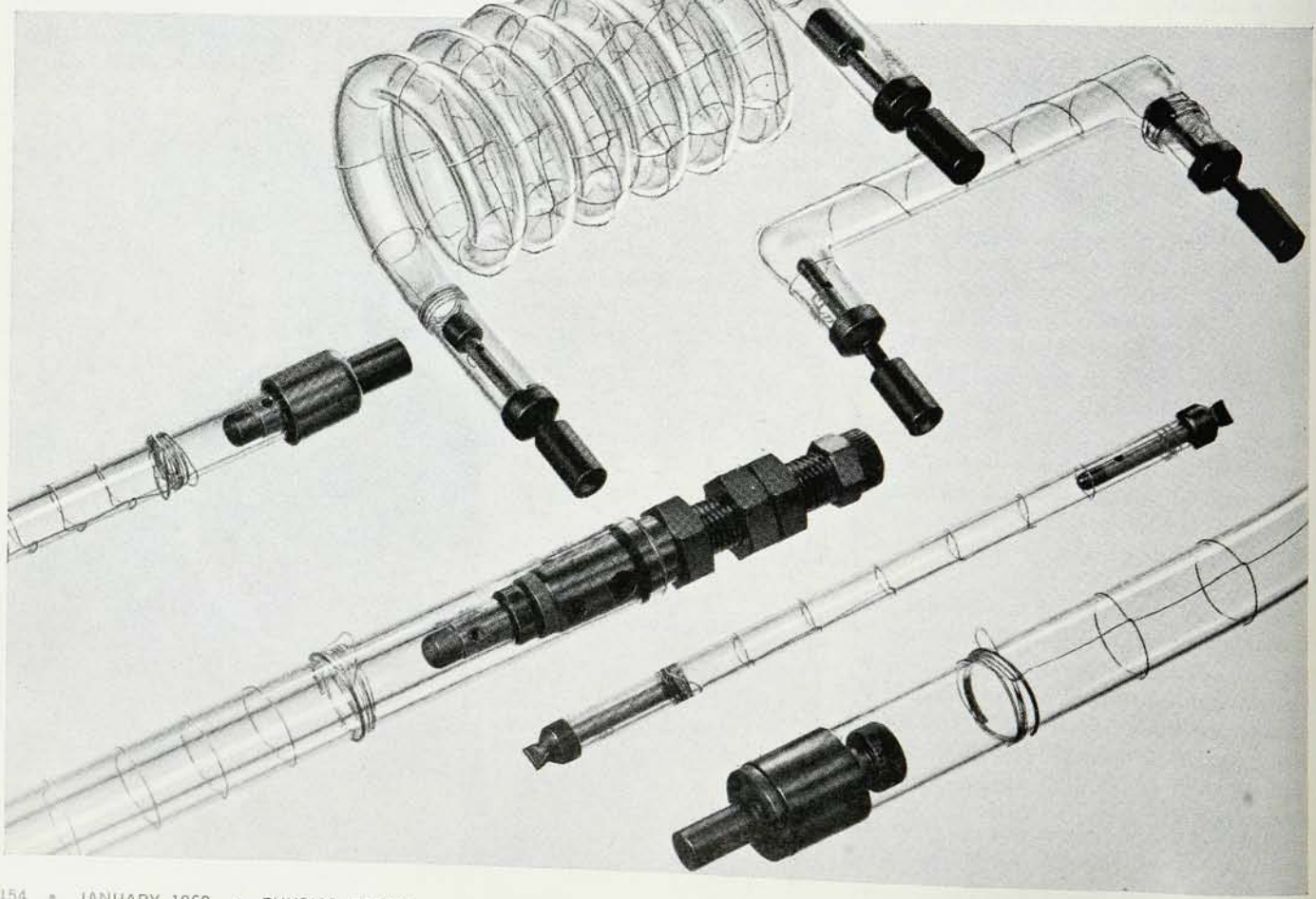


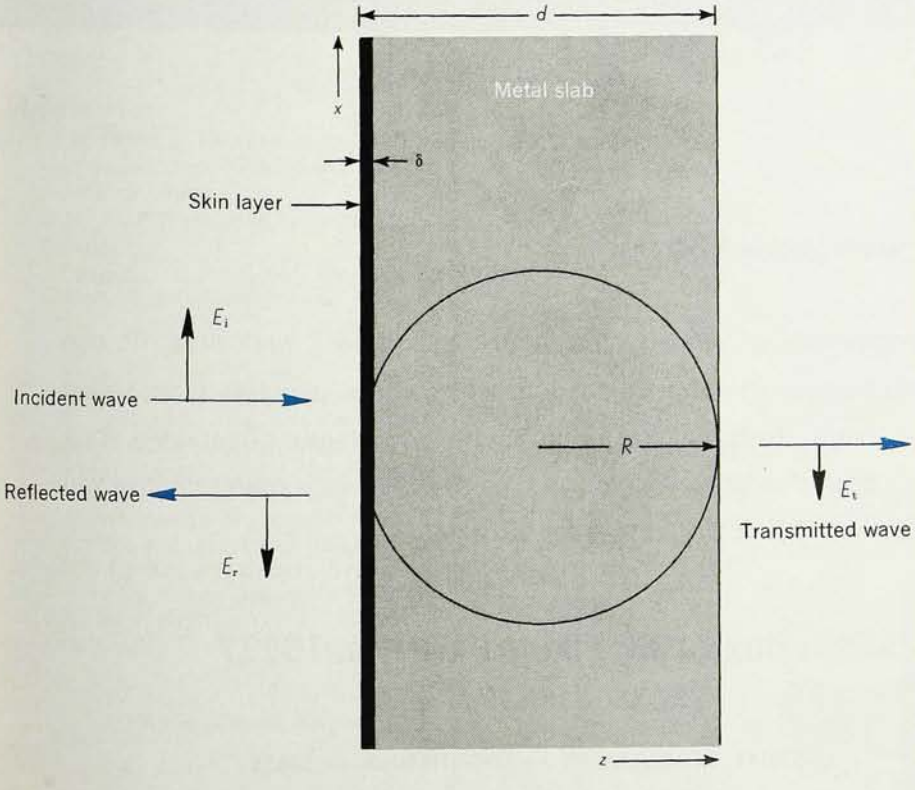
time variation of electric field in the skin layer and hence make an anomalously large contribution to the currents flowing in the skin layer, figure 1. As a result, the surface impedance of the metal displays well defined minima (a reduction in the amplitude of the net electric field at the surface of the metal) whenever $\omega_c = \omega/n$, where $\omega$ is the frequency of the incident radiation and $n$ is an integer.

*Spatial resonances*

The second type is exemplified by Gantmakher resonances. Here the steady magnetic field is parallel to the surface of the specimen, just as it is for cyclotron resonance experiments, but the frequency of the applied radiation is low (usually 1–10 MHz) so that $\omega_c/\omega \gg 1$. Electrons that return to the skin layer several times in succession experience an electric field that, to all intents and purposes, remains constant in amplitude and phase. As a result of multiple passages through the skin layer, electrons carry currents into the metal to a depth given by their cyclotron diameters, $2R$. If a large number of carriers have the same cyclotron diameter they create a current layer a distance $2R$ from the surface of the metal. This current layer, which is an attenuated image of the original current sheet at the metal surface, is itself imaged a distance $2R$ further into the metal, and so on. A series of current sheets of successively diminishing amplitude is therefore set up in volume of the metal.

Whenever one of these current sheets coincides with the back surface of a specimen of finite thickness $d$ it radiates away some energy and the metal slab becomes slightly transmitting, figure 2. The resonant condition $2R = d/n$, where $n$ is an integer, can be detected either as an increase in transmitted radiation or as a concomitant increase in the surface impedance of the specimen. Of course both cyclotron resonances and Gantmakher resonances can only be observed in very pure metals for which $R/l \gg 1$, where $R$ is the cyclotron radius of the

**SPATIAL RESONANCE or Gantmakher resonance. A static magnetic field is applied along the $y$ axis. When the diameter of the cyclotron orbits of a group of carriers can just be fitted between the surfaces of a metal slab some energy is carried from the skin layer and radiated away at the back surface. Some energy is transmitted at the harmonics but with weaker intensity. —FIG. 2**



carriers at the value of the field for which resonance occurs.

The surface impedance of a metal exhibits a rich variety of effects when the steady magnetic field is tilted out of the plane of the specimen; Walsh discussed these effects using data primarily for potassium and sodium. It was particularly exciting to hear of the work he and his collaborators have been doing on wave propagation in sodium and potassium near Azbel'-Kaner cyclotron resonance, and also about the conduction-electron spin-resonance sidebands discovered recently in sodium and potassium by Sheldon Schultz and Gerald Dunifer at La Jolla.[3] So far these experiments are the only ones that have explicitly required many-body interactions for their explanation.

It was the aim of this summer school on electrons in metals to provide an overall appraisal of current Fermi-surface research, as well as to provide a quiet and relaxing environment in which experts in a given field of specialization could discuss their problems.

Judging from the comments of the participants, these aims were successfully met. In fact, the meeting was so successful that it is planned to hold an annual summer school at Alta Lake although the topics to be discussed will range over the whole of solid-state physics.

*References*

1. A. B. Pippard, *The Dynamics of Conduction Electrons* (Gordon and Breach, New York) 1965.
2. T-W. Nee, R. E. Prange (to be published).
3. S. Schultz, G. Dunifer, Phys. Rev. Letters **18**, 283 (1967).

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