Evidence for a Temperature-Dependent Surface Shielding Effect in Cu†

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A large temperature-dependent transition in the magnitude of the ambient axial electric field inside a vertical copper tube has been observed. Above a temperature of 4.5 K the ambient field is 3×10^{-7} V/m or greater. Below 4.5 K, the magnitude of the ambient field drops very rapidly, reaching about -5×10^{-11} V/m at 4.2 K. We believe that these effects results from the presence of a surface electron layer on the inside wall of the tube which provides a temperature-dependent shielding effect.

A discrepancy has existed for several years between the results of the measurement by Witteborn and Fairbank (WF)[1] of the total force felt by an electron traveling along the axis of a vertical copper tube and the expected magnitude of the ambient electric field in the tube. WF measured a net force on the electron of zero to within $\pm 6\times10^{-12}$ V/m; this value was interpreted to be the result of the combined effects of gravity on the test electron and an ambient electric field of about -5×10^{-11} V/m. Theoretical predictions and room-temperature contact-potential results indicated that an ambient field of 10^{-6}–10^{-7} V/m should be present. We have measured the ambient electric field present in the tube used by WF at several temperatures between 4.2 and 300 K and have found that the magnitude of the field makes a sudden transition at 4.5 K from a value consistent with that observed by WF to a value roughly four orders of magnitude larger.

At least two mechanisms act to produce an ambient electric field in a vertical metal tube. First, the fact that the tube is composed of many small crystallites results in the existence of a spatially fluctuating "patch effect" field along the axis of the tube; the rms magnitude of this field is expected to be about 10^{-6} V/m unless some ordering in the distribution of different kinds of crystallites is present. Second, the effect of gravity on the ionic lattice and the electron gas of the metal produces a uniform axial electric field in the tube.

The magnitude of the gravitationally induced field in a vertical metal tube was first calculated by Schiff and Barnhill,[2] who obtained the value mg/e, where m is the electron mass; this result implies that an axial field is produced by the gravitationally induced redistribution of metallic electrons but not by the differential compression of the ionic lattice caused by gravity. However, Dessler, Michel, Rorschach, and Trammell[3] (DMRT) were able to show that the lattice compression should produce a much larger field Mg/e where M is the ionic mass. Later, Herring[4] was able to reconcile the DMRT result with the approach taken by Schiff and Barnhill by taking into account certain surface effects. Other models were explored by Peshkin,[5] Rieger,[6] and Leung, Papini, and Rystephanick.[7] Several room-temperature experiments were then conducted to search for stress-induced contact-potential variations in various metals; Beams,[8] Craig,[9] and French and Beams[10] performed much of the early work. The results were in general consistent with the DMRT calculation (some of the difficulties in the interpretation of such measurements have been pointed out by Enga[11]). By this time though, considerable supporting evidence for the validity of the WF result was available. The experiment itself yielded the proper e/m for the electron, and a related experiment measured the anomalous magnetic moment of the electron.[12] Also, the correct value of g was obtained in experiments with ions.[13] It appeared that the low-temperature environment in which the WF experiment was conducted might have been crucial to its success. This idea led to our program of experiments in which slightly modified versions of the WF apparatus and technique were used to measure the ambient field in the copper tube at 300, 77 K, and several temperatures between 4.2 and 11 K.

Both the original apparatus and technique used by WF and the more recent modifications are described in detail elsewhere.[14,15] The current version of the apparatus is illustrated in Fig. 1. Basically the electric field present inside a vertical electrostatic shielding tube is determined by its effect on the time of flight of a very slow electron which travels along the tube axis. A burst of low energy (< 1 eV) electrons is emitted from a pulsed tunnel cathode and guided through

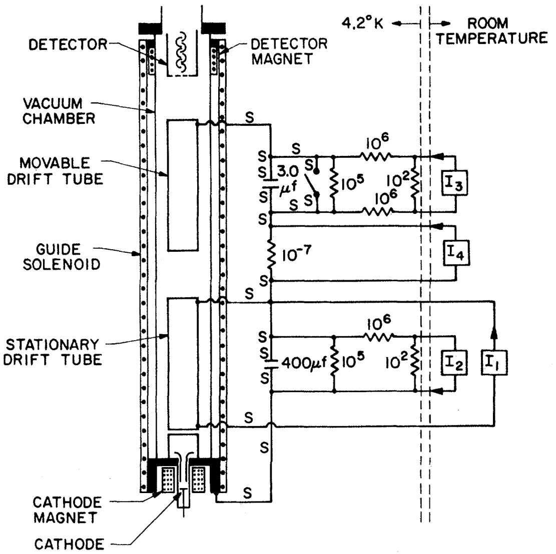

FIG. 1. A schematic diagram of the electron time-of-flight apparatus and the associated electrode biasing circuitry. Wires and capacitors labeled s are superconducting in order to eliminate Johnson noise. I_1–I_4 are constant current power supplies.

the tube by a superconducting solenoid to a windowless photomultiplier detector. Electrical biasing is arranged so that the electrons of interest travel slowly only while inside the shielding tube. Detector pulses are stored in a multichannel analyzer in a channel appropriate to the time of flight through the drift tube. The experiment is repeated many times until a distribution of flight times is obtained. A uniform applied electric field can be established in the tube by passing an axial current through the walls. The 300 and 77 K measurements were made with copper wire magnets and conventional electrode biasing circuitry (and thus with more noise and decreased sensitivity). The measurements in the range 4.2–11 K were made with all of the apparatus at 4.2 K except for the thermally isolated shielding tube so that the advantages of cryopumping and superconducting magnets and circuitry could be retained. The tube was resistively heated in such a manner as to minimize thermal gradients; its temperature was monitored by a carbon resistor thermometer.

At each value of temperature data were taken with four different values of applied electric field, one of which was always zero. The applied field was cycled through each of the four values many times during each run at a given temperature in order to average out the effects of long term drifts in experimental conditions.

The time-of-flight spectra which were obtained in these runs were analyzed to determine the ambient electric field present in the tube at each temperature. The time of flight for an electron which enters the tube with energy W is given by

$$t=\left(\frac{m}{2}\right)^{1/2}\int_0^h \frac{dz}{[W-ezE_{\text{amb}}(z)-ezE_{\text{app}}-mgz]^{1/2}}, \tag{1}$$

where h is the length of the tube, E_{amb} is the effective ambient electric field (assumed to consist of a constant term due to gravitationally induced distortion of the tube and a term due to the patch effect with a complicated z dependence), and E_{app} is the applied uniform field. In the room-temperature and 77-K work it was only possible to determine t when E_{app} was significantly greater than E_{amb}, so the determinations of E_{amb} had relatively large errors. In the 4.2–11-K work it was possible to determine E_{amb} directly by comparing spectra obtained at the same temperature with different values of E_{app}. The spectra are complicated by the effects of fringing fields and the delayed emission of electrons from electrostatic and magnetic potential traps; however, it proved possible to determine the ambient field values with sufficient accuracy to make the nature of the temperature transition in the shielding rather clear.

The results obtained at all the different temperatures studied are plotted together in Fig. 2. An exact comparison of the results at 300 and 77 K with the results from the range 4.2–11 K is difficult since both the data-analysis techniques and the detailed nature of the apparatus were different in the two regions; however, an order of magnitude comparison can be made. We find the effective ambient field at room temperature to be $(7.5\pm 6)\times 10^{-6}$ V/m; at 77 K the value is $(4\pm 2)\times 10^{-6}$ V/m. In these cases we are not able to say whether these values correspond to the magnitude of a gravitationally induced uniform field or the rms level of a spatially fluctuating patch-effect field; the latter seems more likely. Because of the manner in which these fields and their errors are determined, the stated error limits are not standard deviations but are more nearly maximum variations of the field. In general the decade in which the ambient field magnitude falls is well known even when the value within the decade is not precisely determined. This

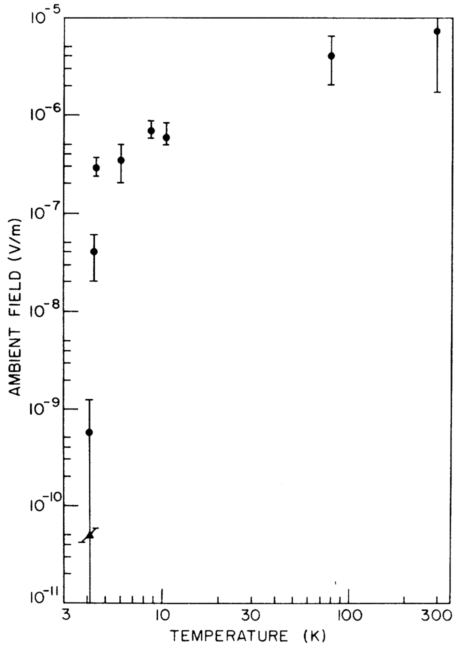

FIG. 2. The ambient electric field in the tube as a function of tube temperature. The closed circles show the present experimental results. The triangle shows the absolute value of the 1967 result of Witteborn and Fairbank, which was -5×10^{-11} V/m at 4.2 K.

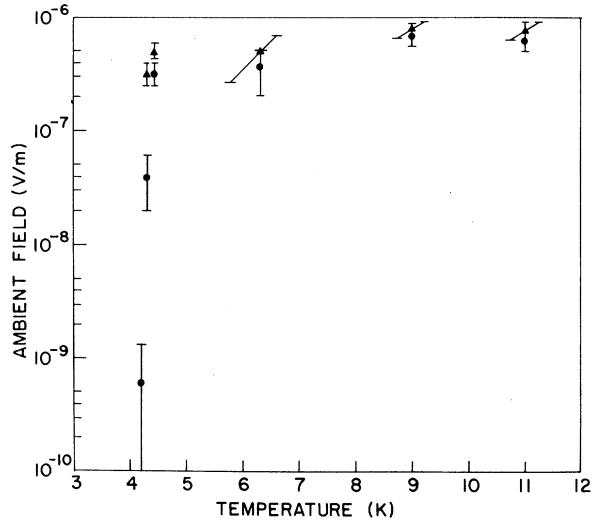

FIG. 3. An expanded view of the low-temperature results. The two sets of points are obtained using different analysis techniques, as described in the text.

means that the error curve is much closer to a rectangle function than a Gaussian.

The results in the region 4.5–11 K show an ambient field about an order of magnitude lower than that present at 77 K; the values here agree quite well with the DMRT prediction of a field of approximately 10^{-6} V/m. Below 4.5 K the very sharp transition in the ambient field can be seen. At 4.2 K we obtained a value of $(6\pm7)\times10^{-10}$ V/m for the ambient field; this is consistent with the more accurate value of $-(5.6\pm0.6)\times10^{-11}$ V/m obtained in the original experiment performed by Witteborn and Fairbank (WF had much more data at 4.2 K, allowing a considerably better determination of the field). The results from the range 4.2–11 K are shown as closed circles on the expanded linear temperature scale of Fig. 3.

In order to further check the 4.2–11-K results presented in Figs. 2 and 3, the time-of-flight data were analyzed by a somewhat different technique. Rather than comparing spectra taken at the same temperature but with different values of applied field in order to determine the ambient field, spectra taken at the same value of applied field but at different values of temperature were compared. This is most logically done for the case of no applied field; the results of the analysis are shown as triangles in Fig. 3. Since this latter analysis technique utilizes less of the available data than the comparison of spectra taken at a given temperature, the results are not expected to be as accurate; however, the two sets of results are in rather good agreement.

It would seem from these results that a highly temperature-dependent shielding mechanism must exist in the tube; at temperatures below 4.5 K the axis is shielded from the patch effect and lattice distortion fields while above 4.5 K the shielding is either nonexistent or only very weakly effective. There is some indication that the patch effect is either partially shielded or else is somehow reduced in magnitude below 77 K. Since the WF experiment saw a field in the tube which implied perfect shielding of the patch effect and lattice distortion fields but which agreed with the estimates for the field produced by the gravitationally induced redistribution of metallic electrons, the shielding must be accomplished by surface electrons. Condensation of residual gas on the drift tube walls is not thought to play an important role in the shielding; only 10^{-6} or so of a monolayer could be condensed since a room temperature vacuum of 10^{-10} Torr is attained before cooldown. It should be mentioned that an examination of the copper surface revealed a layer of copper oxide approximately 20 Å thick. We assume that the electrons responsible for the shielding exist on the surface of the oxide and that the oxide serves to decouple the surface electron energy levels from the band structure of the bulk copper. It is interesting to note that the tube axis is not shielded from the field produced by passing an axial current through the walls of the tube. A search is now in progress for a theoretical model for this dramatic shielding effect.[16]

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Nonlinear Optical Excitation of Surface Exciton Polaritons in ZnO

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Dispersion and damping characteristics of surface exciton polaritons in ZnO have been measured by nonlinear optical technique. Optical mixing was used to excite surface exciton polaritons while surface roughness was used to couple the surface waves out. The results were used to deduce characteristic parameters of bulk excitons in ZnO.

The surface exciton polariton has long been a subject of extensive theoretical studies.[1] Experimental research on the subject has however been very rare. So far as we know, Lagois and Fischer[2] have conducted the only measurement of exciton polariton dispersion in ZnO using the method of attenuated total reflection (ATR). The difficulty lies in the fact that excitons usually exist at low temperatures and the ATR method is not easily applicable to surface polaritons with relatively short wavelengths. We have recently proposed that surface polaritons can be investigated by nonlinear optical techniques.[3-5] In this Letter, we report the first experiment on nonlinear optical excitation of surface exciton polaritons. We show that the surface exciton polariton waves are radiative because of surface roughness,[6] and detection of the radiative surface waves enables us to measure both dispersion and damping of the surface exciton polaritons.

Surface polaritons only exist in the reststrahlen band of a crystal. For a semi-infinite anisotropic crystal b bounded by an isotropic medium a, the dispersion relation for polaritons is given[7]