PHYSICAL REVIEW
LETTERS

VOLUME 30 11 JUNE 1973 NUMBER 24

# Field Emission of Hot Electrons from Tungsten*

Martin J. G. Lee
*The James Franck Institute and The Department of Physics, The University of Chicago, Chicago, Illinois 60637*
(Received 5 March 1973)

Field emission of hot electrons is observed from a laser-illuminated tungsten tip. The field dependence of the total current is accurately described by a simple theory of barrier penetration.

The purpose of this Letter is to report a study of the field emission of excited ("hot") electrons from tungsten. In the present experiments, a distribution of hot electrons was produced by illuminating the field emitter with photons of energy somewhat smaller than the work function. Under these conditions, two processes of field emission can be distinguished. If the applied field is sufficiently small, emission of hot electrons can proceed only by tunneling through the triangular potential barrier at the surface of the metal. As the electric field is increased, the peak of the barrier is lowered by the Schottky effect,[1] and eventually direct emission over the peak of the barrier is expected to predominate. This transition has been observed in the present experiments, where it leads to a qualitative change in the shape of the Fowler-Nordheim plot of the hot-electron current.

The apparatus consisted of a field-emission tube fitted with quartz windows, and a retardation analyzer. A small portion of the electron beam from the emitter was permitted to pass through a 2-mm hole in the fluorescent screen. It was then focused by an Einzel lens and impinged normally on a biased Lektromesh screen which served as the retarder. Those electrons having sufficient total energy to pass through the screen were collected by a Spiraltron multiplier, and were counted as individual pulses. The total-energy distribution was obtained by low-frequency modulation of the retarding bias. The background count rate was about 1 electron per second. Electrostatic deflection electrodes mounted close to the emitter permitted the positioning of any desired region of the field-emission pattern over the probe hole. In order to achieve paraxial beams, the emitter assembly could be shifted slightly by means of a bellows arrangement. In the experiments reported here, the light source was an argon-ion laser. The laser beam was filtered to remove fluorescence radiation and focused onto the tip, which was cooled by contact with liquid nitrogen. Emission of hot electrons was studied with exciting radiation in the near ultraviolet (radiation at 3.531 eV mixed with radiation at 3.408 eV), and in the visible (at 2.602 eV). The luminous intensity at the tip was approximately 3 kW/cm$^2$ in the ultraviolet, and 10 kW/cm$^2$ in the visible.[2]

A plot of the total-energy distribution in the direction of strongest emission, corresponding to emission from a small region of the tip close to the (310) crystal planes, was observed in the absence of illumination, and is shown in Fig. 1. The peak on the right corresponds to tunneling from the Fermi distribution within the metal. The position of the Fermi level was estimated

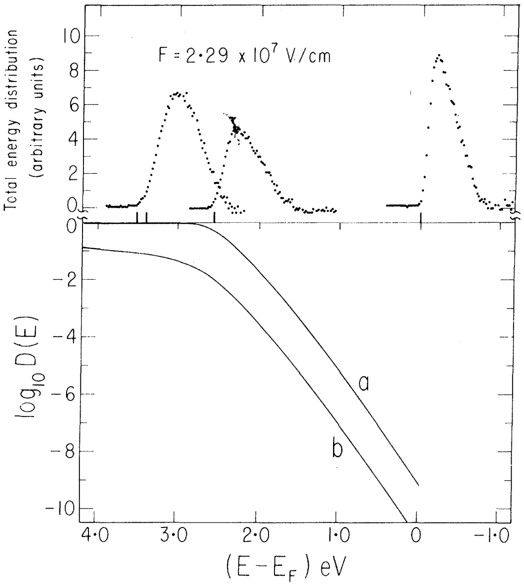

FIG. 1. Total-energy distributions for field-emitted electrons from tungsten. The peaks on the left and in the center correspond to emission from the hot-electron distributions in the metal, and that on the right corresponds to field emission from the Fermi distribution. The lower curves are the barrier penetration factors calculated according to the assumptions of (a) Eq. (3a) and (b) Eq. (3b).

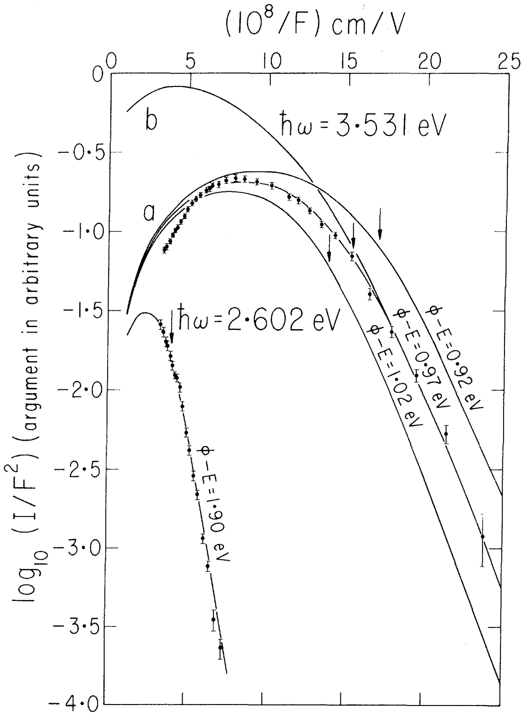

FIG. 2. Fowler-Nordheim plots of the total hot-electron current from a small region of the tungsten field emitter close to (310), and comparison with the theory described in the text. The arrows indicate the minimum field strength at which excited electrons can skim over the surface barrier. Curve *a* was calculated from Eq. (3a), and curve *b* from Eq. (3b).

by comparison with theoretical curves given by Young.[3] From the shape of the leading edge, the resolution of the energy analyzer was found to be ~0.10 eV. The other two peaks correspond to emission from the hot-electron distribution. The peak on the left appears when the tip is illuminated with the ultraviolet radiation. The highest electron energy in the distribution is ~3.5 eV above the Fermi level, which is consistent with the photon energy. The leading edge of this peak is broader than the leading edge of the direct-emission peak, presumably because of the energy dependence of the barrier penetration factor, and because the radiation is nonmonochromatic. The peak in the center appears when the tip is illuminated with 2.602-eV radiation, and again the highest energy in the distribution is consistent with the photon energy. The leading edge of this peak also is somewhat broader than the leading edge of the direct-emission peak.

In order to establish the nature of the field-emission processes leading to the observed peaks, the total hot-electron current in the direction of strongest emission was studied as a function of the applied electric field. The constant $\alpha$, which relates the electric field at the tip to the potential difference between the tip and screen ($F = \alpha V$), was estimated from the field dependence of the total tunneling current in the usual way.[4] Fowler-Nordheim plots of the total hot-electron current at the two photon energies are shown in Fig. 2. The slope in the low-field region is consistent with the view that emission takes place by tunneling, with an effective work function $\varphi - E$, where $\varphi$ is the work function of the tip and $E$ is the maximum hot-electron energy measured from the Fermi energy.[5] In the high-field region the slope of the Fowler-Nordheim plot changes sign. This effect marks the transition to predominant field-induced photoemission above the peak of the Schottky barrier.

In order to describe quantitatively the field dependence of the total hot-electron current, the theory of penetration of the surface barrier developed by Murphy and Good[6] was used. This theory has also been applied to the hot-electron problem by Neumann[7] and Klein,[8] and by Polizzotti, Liu, and Ehrlich,[9] and is known to give a satisfactory account of the total-energy distribution in thermal field emission.[10] The barrier penetration factor depends only on the normal energy $W$, and can be written

$$D(W)=\{1+\exp[A(W)]\}^{-1}, \tag{1}$$

where

$$A(W)=\frac{4}{3}\left(\frac{2m}{\hbar^2}\right)^{1/2}\frac{(E_{\mathrm{F}}+\varphi-W)^{3/2}}{eF}\times U\left(\frac{(e^3F)^{1/2}}{E_{\mathrm{F}}+\varphi-W}\right) \tag{2}$$

and the Nordheim function[11] $U(y)$ takes into account rounding of the tunneling barrier by the Schottky effect. Equation (1) is expected to fail whenever $y>\sqrt{2}$. For the corresponding normal energies, which are well above the peak of the barrier, the penetration factor $D(W)$ can be set equal to one. If it is assumed that the hot-electron distribution is created by transitions to states of normal energy $W(E)$, then the current of hot electrons of total energy $E$ is proportional to[12]

$$D(E)\equiv D(W(E)). \tag{3a}$$

If instead it is assumed that the hot-electron distribution is created by transitions to states having a free-electron–like distribution of normal energies, then the current of hot electrons of total energy $E$ is obtained by integrating the penetration factor over a uniform distribution of normal enegies. It is proportional to[13]

$$D(E)\equiv(E-E_0)^{-1}\int_{E_0}^{E}D(W)\,dW, \tag{3b}$$

where $E_0$ is the energy of the bottom of the band. In Fig. 1, the functions $D(E)$ calculated from Eqs. (3a) and (3b) are plotted for $F=2.29\times10^7$ V/cm and $\varphi=4.35$ eV, which are the conditions of the experimental total-energy distributions. Under these conditions, the peak of the surface barrier lies 2.53 eV above the Fermi level.

The total hot-electron current $I$ is given by

$$I=\int_{-\infty}^{E}N(E')D(E')\,dE', \tag{4}$$

where $N(E')$ is the total-energy distribution of hot electrons within the metal, and $E$ is the highest energy in the total-energy distribution. In order to evaluate $I$ by numerical integration of Eq. (4), a uniform total-energy distribution was assumed. Then the field dependence of $I$ is a function of the single parameter $\varphi-E$. Fowler-Nordheim plots of the total hot-electron current, calculated from Eqs. (1)–(4) for different values of $\varphi-E$, have been compared with the experimental data. In low fields, such that emission takes place below the peak of the surface barrier, the theoretical curves are independent of the assumed normal-energy distribution. The closest agreement with the experimental data was found with $\varphi-E=0.97$ eV in the ultraviolet, and $\varphi-E=1.90$ eV in the visible. Assuming $E=\hbar\omega$, one finds in each case $\varphi=4.50$ eV. This result can be compared with the work function determined from a Fowler-Nordheim plot of the direct field-emission current from the same region of the tip: $\varphi=4.35\pm0.05$ eV. For energies close to the peak of the surface barrier, the resolution of the field-emission microscope depends on the electric field, and precise agreement between the work functions obtained by the two techniques would be fortuitous. Calculations show, however, that even for hot electrons the circle of confusion in the present experiments is never larger than the probe hole.

In high fields, such that emission takes place above the peak of the surface barrier, the theoretical Fowler-Nordheim curves depend sensitively on the assumed distribution of normal energies. In Fig. 2, Fowler-Nordheim curves that correspond to the assumptions of Eqs. (3a) and (3b) are compared with the experimental data. The assumption of a narrow distribution of normal energies is in better agreement with the data. In order to evaluate Eq. (4), a uniform total-energy distribution of hot electrons within the metal was assumed. A uniform normal-energy distribution together with a narrow total-energy distribution could equally well account for the observed field dependence of the hot-electron current. However, this possibility is inconsistent with the broad experimental total-energy distributions shown in Fig. 1. Structure in the total-energy distribution might account for departures from the theoretical Fowler-Nordheim curves in the high-field region, but changes in resolution could also contribute to these effects.

As has been stressed by Lundqvist, Mountfield, and Wilkins,[14] interest in field emission of hot electrons lies in its potential for the spectroscopy of excited states in metals. An accurate description of the transmission properties of the surface barrier is an essential first step in the development of this technique. The present observations of the total hot-electron current from close to the (310) crystal planes of tungsten agree well with a theory based on the penetration factor derived by Murphy and Good. The data in the high-field region suggest that optical transitions take place to states having a narrow distribution of normal energies. The small discrepancy in the absolute work function is consistent with transitions to states whose normal energies are somewhat less than their total energies, or with partial suppression of transitions from the top of the Fermi distribution. At each photon energy, the onset of the experimental total-energy distribution in Fig. 1 is close to $E_F + \hbar\omega$. It is difficult to reconcile this behavior with a two-step process involving an intermediate $k$-conserving transition to an excited band state of the metal, as the probability of an allowed transition from the Fermi energy at an arbitrary photon energy is small. It seems likely that emission occurs as a result of $k$-nonconserving transitions to final states that are evanescent within the metal. The nature of the observed transitions will be further explored by studying the anisotropy and field dependence of the hot-electron total-energy distribution.

I am indebted to Stuart Solin for helpful discussions of various problems in optics, and to Robert Gomer for help with the design and construction of the experimental apparatus and for critical comments on the manuscript.

*Work supported by a Research and Study grant from the General Electric Company, and benefitted from the general support of the Materials Research Laboratory by the National Science Foundation.

[1] R. H. Good and E. W. Müller, in *Handbuch der Physik*, edited by S. Flügge (Springer, Berlin, 1956), Vol. 21, p. 183.

[2] The estimated temperature of the tip under these conditions is 130°K with ultraviolet illumination, and 400°K with visible illumination.

[3] R. D. Young, Phys. Rev. 113, 110 (1959).

[4] Ref. 1, p. 194. The average work function was assumed to be 4.50 eV.

[5] Ref. 1, p. 194.

[6] E. L. Murphy and R. H. Good, Phys. Rev. 102, 1464 (1956).

[7] H. Neumann, Physica (Utrecht) 44, 587 (1969).

[8] H. Neumann and Ch. Kleint, Ann. Phys. (Leipzig) 27, 237 (1971).

[9] R. S. Polizzotti, R. Liu, and G. Ehrlich, in Proceedings of the Nineteenth Field Emission Symposium, Urbana-Chapaign, Ill., 1972 (unpublished).

[10] J. W. Gadzuk and E. W. Plummer, Phys. Rev. B 3, 2125 (1971).

[11] Ref. 1, p. 187.

[12] In calculations based on Eq. (3a) we have assumed $W(E) = E$.

[13] In calculations based on Eq. (3b) we have taken the width of the normal-energy distribution to be 1.2 eV. Increasing the width does not significantly affect the results.

[14] B. I. Lundqvist, K. Mountfield, and J. W. Wilkins, Solid State Commun. 10, 383 (1972).

---

# Phonons and Phase Transitions of Helium*

Daniel C. Mattis and Leon F. Landovitz
*Belfer Graduate School of Science, Yeshiva University, New York, New York 10033*

(Received 5 March 1973)

We find a new collective shear-wave—like mode above $T_\lambda$, merging with the longitudinal acoustic mode at a higher critical temperature. The speed of the new sound wave is predicted to vanish near $T_\lambda$ as $s \propto (T - T_\lambda)^{\frac{1}{2}}$.

Whereas the ideal Bose-Einstein gas sheds little light on the complex properties of liquid helium, beyond exhibiting a third-order phase transition to a condensed phase[1] (at, however, the wrong temperature), by contrast the weakly nonideal fluid displays a wealth of dynamical and thermodynamical structure. By studying collective modes we have been able to identify a gas phase, a normal fluid phase, and a superfluid phase. The present study concentrates on the higher-temperature phases, corresponding to He I at and above $T_\lambda$, and the transition to a gas phase at $T_b$. In the fluid phase we obtain two solutions corresponding to a longitudinal and a transverse mode of acoustic propagation. The latter seems related to the anomalies at the superfluid transition temperature, for its speed of propagation vanishes at $T_\lambda$ and fits the law

$$s \propto (T - T_\lambda)^{1/2} \quad (T \gtrsim T_\lambda). \tag{1}$$

Thus at $T_\lambda$ the system becomes unstable against an arbitrary number of long-wavelength excita-