

Measurement of multiple-electron emission in single field-emission events

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Thermal and field electron emission from a modified electron microscope W source were measured with an energy-dispersive counting system. Thermal-emission spectra were consistent with random emission of single electrons, while field-emission spectra were consistent with multiple-electron emission in random events. As many as 11 electrons were detected in isolated random field-emission events. © 1997 American Institute of Physics. [S0021-8979(97)06023-4]

Most measurements of electron field emission (FE) are made with retarding field spectrometers and current measuring devices. It is impossible to determine how many electrons are emitted in a single FE event with these instruments. Herrmann and, later, Gazier first looked at individual events using energy-dispersive detectors.^{1,2} For example, Gazier measured FE from W, W(Th), Pt, and Cu with an energy-dispersive Si(Li) spectrometer. Gazier's pulse height spectra, which indicated simultaneous arrival of as many as six electrons, were not consistent with random emission of single electrons.² Fursei and co-workers have carried out numerous experiments to measure FE electron statistics under a variety of experimental conditions, and have published extensively on this subject since 1975.³⁻¹⁴ Their first results indicated multiple emission from W and Si.³ However, in an experiment to measure FE from various facets of a clean W single crystal and at high vacuums, only single electron emission was observed.⁵ In a 1991 paper that reviewed much of the work of Fursei and his colleagues, Fursei supposed that Gazier's multiple emission peaks were a result of parasitic secondary electron emission from the intermediate electrodes, and he concluded on the basis of many experiments that FE has a single particle character.¹⁴

Prompted by an unpublished experiment carried out by one of us (P.J.E.) at the Lawrence Livermore National Laboratory (LLNL) which supported Gazier's results,¹⁵ James and co-workers undertook similar experiments with a thin-window proportional counter.¹⁶⁻¹⁸ Their results also supported Gazier's experiment. Some experimental results are listed in Table I. Secondary electron emission caused by back-streaming ions impacting the cathode was judged not to be a cause of the multiple electron peaks.¹⁵ We are not aware of any theoretical treatment of this phenomenon.

This article is a report of energy dispersive measurements of thermal emission (TE) and FE from single, isolated W tips. The experiments were undertaken in an attempt to clarify a rather confusing experimental situation and to identify the source of multiple-electron emission. A Siemens

Elmiskop II transmission electron microscope was modified for this purpose. The electron source was standard, a commercially available W point filament that could be heated to 2800 K. Thus, the filament could be either a TE or FE source. It was positioned in the high field acceleration region of the microscope, through the cathode's aperture. There were no intermediate electrodes between the tip and the anode, which was held at ground potential. All beam optical components such as apertures and magnetic lenses were downstream of the anode. To center the beam on the axis of the microscope, the tip could be shifted in relation to the anode in two normal directions without breaking vacuum. The microscope, operated at 50 kV, was evacuated with an oil-diffusion pump. Typical operating pressure was 5×10^{-5} Torr or below. The microscope column had to be extended to accommodate a 25 mm² Si surface barrier detector that could be translated 100 mm along a horizontal axis. The detector was 595 mm from the tip, and was collimated with a 3 mm diameter iris to reduce the active detection area and to improve spatial resolution. The dimensions of the electron beam were controlled with the magnetic lens, and could be viewed with a retractable phosphorescent screen located 23 mm upstream of the detector. Charge pulses from the detector were processed in a counting system consisting of a preamplifier, a main amplifier, a multichannel analyzer, and a count rate meter. Amplified pulses ($\sim 3 \times 10^{-6}$ s) were also monitored with an oscilloscope.

Because the spectra reported herein have unusual characteristics (up to 11 electrons arriving simultaneously), it is important to briefly consider the characteristics of our counting system. A count is a pulse that is registered in response to the deposition of energy in the detector. The detector is energy dispersive and linear, that is, the amplitude of the charge pulse generated in it is directly proportional to the energy deposited by the electron(s). Also, there is a fixed minimum time interval that separates two events such that they are recorded as separate pulses. During this interval, the system is "dead." Two electrons arriving during the dead time are recorded as a sum pulse, that is, a single pulse with twice the energy. We were concerned that the counting sys-

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TABLE I. Compilation of experimental results.

| Experimenters | T_c (kV) | Z | N^a | n^b | P (Torr)/ T (K) | Detector comments |
|-----------------------|------------|--|-------|-------|-------------------------|---|
| Herrmann ^c | 15 | W | 1 | 1 | $10^{-6}/300$ | Proportional ctr. |
| Gazier ^d | 40 | W(Th) | 5 | 1.3 | $10^{-6}/300$ | Cooled Si(Li) |
| Gazier | 40 | W | 5 | 1.5 | $10^{-6}/300$ | Cooled Si(Li) |
| Gazier | 40 | Pt | 6 | 1.5 | $10^{-6}/300$ | Cooled Si(Li) |
| Gazier | 40 | Cu | 3 | 1.24 | $10^{-6}/300$ | Cooled Si(Li) low count rate |
| Fursei ^e | 12 | Si | 4 | 1.41 | $10^{-9}/300$ | Si-surface barrier |
| Fursei ^f | 12 | W | 2 | 1.03 | $10^{-9}/300$ | Si-surface barrier |
| Fursei ^g | 17 | W | 1 | 1 | 10^{-10} 77–1000 K | Si-surface barrier; many facets of clean W single crystal |
| Fursei ^h | 10 | W | 1 | 1 | 10^{-9} | Si-surface barrier; high current, $\Delta t = 10^{-10}$ s |
| Fursei ⁱ | 20 | Ceramic YBa ₂ Cu ₃ O _{7-δ} | 4 | 1.1 | 10^{-9} 4.2 K | Si-surface barrier, $B = 1$ T |
| Ebert ^j | 30 | W | 6 | 1.7 | $10^{-4}/300$ | Proportional ctr. |
| Ebert | 40 | W | 6 | 1.4 | $10^{-4}/300$ | Proportional ctr. |
| Ebert | 40 | W | 8 | 1.5 | $10^{-6}/300$ | Cooled Si(Li) $\Delta E \sim 1$ keV |
| James ^k | 9–30 | W | 6 | 1.4 | $10^{-6}/300$ | 75 μ m diam prop. ctr. |
| This work | 50 | W | 11 | 1.6 | $10^{-5}/300$ | Si-surface barrier |

^aNote that N = number of multiple electron peaks in the measured spectrum.

^bNote that n = average number of electrons detected per count in the measured spectrum.

^cReference 1.

^dReference 2.

^eReference 3.

^fReference 4.

^gReference 5.

^hReferences 10 and 11.

ⁱReference 9.

^jReference 15.

^kReferences 16–18.

tem might have been overwhelmed by the high rates at which data were accumulated, thereby giving rise to an inordinately large number of sum pulses.

Let the system resolving time be t , and the count rate for random emission of single electrons be r . Then the probability of detecting n electrons within t is given by

$$P_n(t) = (2rt)^n/n! \quad (1)$$

and $R_e(n)$, the expected ratio of counts of n electrons to single electron counts is

$$R_e(n) = P_n/P_1 = (2rt)^{n-1}/n! \quad (2)$$

Values of $R_e(n)$ for $n \leq 6$ are given in Table II for system resolving time of 3×10^{-6} and two vastly different count rates (15 and 16 500 counts/s) for which electron energy

TABLE II. Expected and measured peak ratios.

| Peak number n | Energy (keV) | 15 Counts/s | | 16 500 Counts/s | |
|--------------------|-----------------|-----------------------|----------------------|----------------------|----------------------|
| | | $R_e(n)$ | $R_m(n)$ | $R_e(n)$ | $R_m(n)$ |
| 1 | 50 | 1 | 1 | 1 | 1 |
| 2 | 100 | 5.0×10^{-5} | 3.0×10^{-1} | 5.0×10^{-2} | 3.5×10^{-1} |
| 3 | 150 | 1.4×10^{-9} | 1.4×10^{-1} | 1.6×10^{-3} | 1.2×10^{-1} |
| 4 | 200 | 3.0×10^{-14} | 7.2×10^{-2} | 4.0×10^{-5} | 5.3×10^{-2} |
| 5 | 250 | 5.5×10^{-19} | 4.0×10^{-2} | 8.0×10^{-7} | 2.0×10^{-2} |
| 6 | 300 | 8.2×10^{-24} | 2.2×10^{-2} | 1.3×10^{-8} | 8.1×10^{-3} |

spectra were accumulated. Count rates were erratic and not controllable over the long term; however, count rates were monitored for stability during data collection. Figure 1 shows spectra acquired with the cathode at room temperature. The 16 500 counts/s spectrum was taken over a 15 min period; the 15 counts/s spectrum was taken over 4.75 h. The lowest energy peak is at 50 keV, and higher energy peaks are at integral multiples of the acceleration voltage. Peaks are ob-

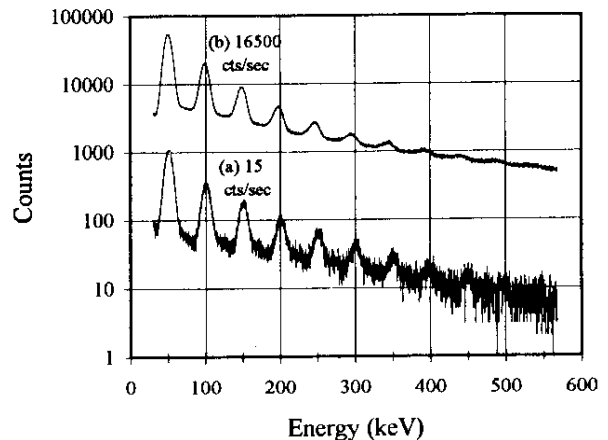


FIG. 1. Pulse height spectra taken from the W filament at room temperature but at different rates: 16 500 counts/s and 15 counts/s.

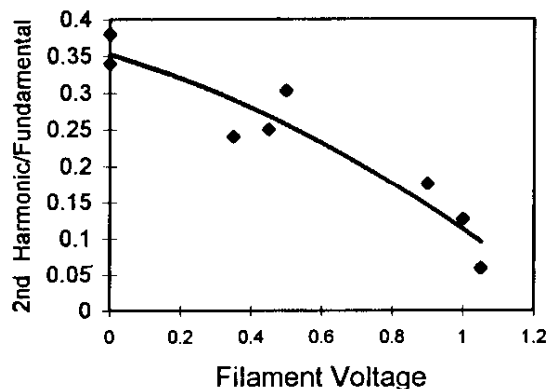


FIG. 2. Ratio of multiple counts to single counts vs filament voltage. Total emission increased with increasing voltage. Thermal emission overwhelmed the counting system with more than 1.1 V applied to the filament.

servable out to 550 keV, but the acceleration voltage was only 50 kV. The two spectra are very much like those obtained by Gazier,² Ebert,¹⁵ and James.¹⁶⁻¹⁸ Note, that in the high count rate spectrum, the peaks are shifted to slightly lower energy and the peak energy resolution is poorer, suggesting that the counting system was well behaved and operating properly. Also note that if the multiple energy peaks resulted from counting random single emission events in coincidence, then $R_m(n)$, the ratio of counts of n electrons to counts of a single electron would also be given by Eq. (2).

Expected values $R_e(n)$ are compared with measured values $R_m(n)$ in Table II. These were obtained by adding counts in each peak and subtracting the monotonically decreasing background. The measured values are orders of magnitude greater than the corresponding expected values. The value $R_m(2)$ at 16 500 counts/s is higher than the corresponding value for 15 counts/s. This is consistent with a higher number of random coincidences at the higher count rate. The differences in $R_m(n)$ for the other harmonics are smaller and are within the experimental errors for these ratios. Also, the average number of electrons detected per event was 1.7 ± 0.1 at 15 counts/s and 1.6 ± 0.1 at 16 500 counts/s. Therefore the multiple energy peaks or sum peaks must be from simultaneous emission of more than a single electron.

The FE rate could be overwhelmed by increasing the filament current, as can be seen in Fig. 2, which plots the ratio $R_m(n \geq 2)$ as a function of filament voltage. At 1.1 V, the emission is 95% thermal.

The electron beam was scanned to demonstrate that the source of multiple-electron emission was the tungsten tip. First, the TE electron source was imaged on the phosphorescent screen, and its position and size checked. The detector (3 mm diam) was then translated through the beam and the beam profile measured. Next, the filament current was turned off, the count rate meter's discriminator was raised to count pulses that were double energy and higher, and the beam profile of double energy and higher FE pulses was measured. The two profiles were virtually identical, as is evident in Fig. 3. The same result was obtained in a second scanning experiment with smaller irises and no magnetic focusing. In these scans, the profiles were wider, but overlaid each other. Thus the TE and FE sources were at the same location; multiple

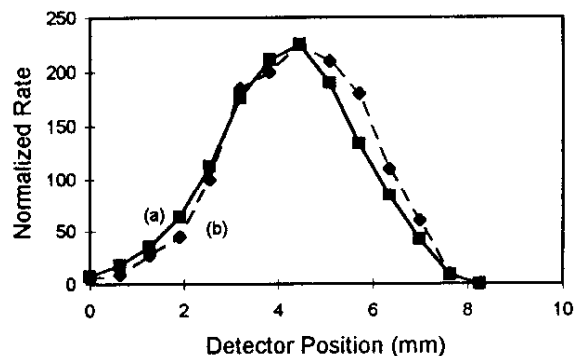


FIG. 3. The normalized rate of electron counts vs detector position for the cases of (a) thermal emission (TE) by counting single emission peaks and (b) field emission (FE) from harmonics above the fundamental, both originating from a W point filament. A 3 mm diam iris was used in measuring the FE and TE intensity profiles.

electron emission spectra were not a result of parasitic secondary electron emission from intermediate electrodes or other surfaces. Therefore, the multiple energy counts recorded must be regarded as detection of integral numbers of FE electrons that originated at the W tip and were detected within the resolving time of the counting system.

It should be noted that the major feature that distinguished experiments that routinely detected multiple emission from those which did not is that an electromagnet focused electrons that were emitted by the source. Another feature is that the vacuums were much poorer than in many of Fursei's experiments.

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