SECONDARY ELECTRONS OF HIGH VELOCITY FROM METALS BOMBARDED WITH CATHODE RAYS

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Abstract

The magnetic spectra of high-speed secondary electrons emitted by Au, Ag, and Al, when bombarded with cathode rays of from 16 to 40 kv., have been photographed and densitometered. Beginning at the high-velocity end, the density is zero down to energy eV_0, equal to that of a primary ray, then rises rapidly to a maximum at about $0.94eV_0$ for Au or Ag, or $0.85eV_0$ for Al, and then declines. The density is everywhere continuous. Its first derivative may be discontinuous at eV_0, but nowhere else.

Thin targets show spectra sufficiently like those of thick targets to indicate that most of the secondary electrons come from very near the surface: for Au, within 0.2 micron even up to 40 kv; for Ag, over 0.2 micron only above 20 kv; for Al, over 0.5 micron only above 20 kv.

Obituary Notice

It is with great regret that we must record the death of the brilliant and promising young scientist whose work is described here. With his great enthusiasm for research, his conscientious thoroughness both instinctive and cultivated by his early education in Germany, and his unusually likable personality, he had every prospect of success and enjoyment in scientific research, and his death was a great loss, both to science and to his friends.

This paper is taken from his thesis for the degree of Master of Arts. As his death occurred in the sinking of the *San Juan*, on his way home to Los Angeles, just after handing in the thesis, he never had an opportunity to condense it for publication. This duty was therefore performed by the instructor, D. L. Webster, with whom he had done the research, but from whom only very little help was ever needed by such an original and able man as Paul Wagner

I. Introduction

Little work has been done on secondary electron emission at voltages ranging from 16 to 40 kv. At lower velocities, 10–12,000 volts, investigation has been carried on by Becker[1] (10–1,000 volts) and by Stehberger[2] (1,000–12,000). Both used the opposing field method. Plotting against the opposing voltage the number of secondary electrons having energy enough to overcome it, Becker obtained, for lower primary velocities, curves of the following general characteristics: for opposing voltages from zero to about 36 volts there is a rapid falling off in intensity; as the opposing voltage reaches higher values the intensity decreases gradually and uniformly, and at an opposing voltage equal to the primary voltage it suddenly drops to zero. This led Becker to distinguish between three types of electrons involved in the process of secondary emission; these he called "secondary" electrons,

[1] A. Becker, Ann. d. Physik **78**, 228 (1925).
[2] K. H. Stehberger, Ann. d. Physik **86**, 825 (1928).

"rediffused" electrons and "reflected" electrons. This classification was accepted by Stehberger. The distinction between secondary and rediffused electrons was based by Becker on the fact that his curves are straight from about 36 volts onward to primary voltages. Denoting by $N(V)dV$ the number of electrons having energies between V and $V+dV$, Becker's curves imply that $N(V)$ is constant except below 36 volts. This constant value gives the number of the electrons Becker calls rediffused; the excess over this, at voltages less than 36 volts, is composed of what he calls secondary electrons. The reflected electrons, finally, are those which have practically the primary energy.

Becker and Stehberger found that the upper limit of energy at which there is an appreciable number of what they call secondary electrons is 36 volts, whatever the nature or thickness of the target and whatever the primary voltage (within the range stated above). They concluded that these secondary electrons are electrons of the target material knocked out by primary and rediffused electrons, that rediffused electrons are primary electrons which have suffered a large number of small encounters with an atomic nucleus. Becker finds that for higher primary velocities the number of reflected electrons diminishes. Stehberger, being unable to apply opposing fields up to the higher primary velocities, made the assumption that reflection completely ceases for these higher primary velocities, basing his assumption on Becker's results for lower velocities.

There is arbitrariness in Becker's distinction between secondary and rediffused electrons, for we are not at all assured that the number of rediffused electrons does remain constant within the interval from zero to 36 volts. In this paper, therefore, the term "secondary" will be used from now on in a broader sense, denoting all the electrons coming from a target bombarded by primary electrons.

M. Baltruschat and H. Starke[3] find that for voltages larger than 6,000 volts the number of fast electrons increases, and that at 30,000 volts even 80 percent of them possess velocities of the order of magnitude of the primary velocities.

Chilinsky[4] did some work on the magnetic velocity spectra of secondary electrons produced from silver by primary electrons of 5 to 20 kv, and found that most of outgoing electrons had velocities about 0.8 of the primary value, and that the intensity in the spectrum fell off sharply at about 0.9 of the primary velocity.

Egon Lorenz[5] carried on investigations, on the x-rays from the back of a tungsten target. He covered a wide range of voltages, up to 83 kv, and compared the spectrum of this so-called "stem-radiation" with that of the focal-spot radiation. The spectra are similar, but the entire stem-radiation spectrum is displaced, towards longer wave-lengths. Thus it approaches the axis at a point which is displaced from the short-wave limit of the focal spot.

[3] Baltruschat and H. Starke, Phys. Zeits. **23**, 403, (1922).
[4] S. Chilinsky, Phys. Rev. **28**, 429 (1928).
[5] Egon Lorenz, Zeits. f. Phys. **51**, 71 (1928).

Beyond this point, it is true, there is a weak intensity extending as far as the focal spot limit, but Lorenz attributes this small amount of radiation to general scattered rays. He then interprets the apparent short-wave limit of the stem radiation by the hypothesis that the primary electrons eject electrons from the L (or other) levels of the target atoms, and that these secondary electrons cause the stem radiation; the short-wave limit of the focal-spot and stem spectra would then differ by just the frequency corresponding to the amount of energy required to extract these electrons. For instance Lorenz observes that at 22.4 kv primary voltage this difference in energy or voltage corresponds to the M level; and at 83.3 kv, to the L level. He states that this can be explained by the known fact "that the greater the energy of rays, the larger is the proportion of them absorbed in higher levels of any series in comparison with that in the other levels." Lorenz concludes that, if the primary cathode-ray energy is about 40 times that of, say, the M level, absorption would cease in that level and proceed to the next higher that is, the L level.

If Lorenz's explanation of his data is correct, it demands revision of current ideas on some other points. Each L electron ejected as a secondary electron must leave an L vacancy in an atom at the focus, and the filling of this vacancy will often, if not usually, cause the emission of a quantum of x-rays of one of the L lines. At 83 kv, an L quantum from tungsten carries off only about a tenth of the energy brought into the focus by the primary cathode ray, and the percentage of L vacancies causing L quantum emission may not be over 50 percent. Even so, however, if the number of secondary electrons is 20 or 30 percent of the number of cathode rays, and if they are chiefly from the L levels, we should expect 1 or 2 percent of the cathode ray energy to reappear as L-series radiation from the focus, as a result of the ejection of only such L electrons as escaped from the target, and much more as a result of the ejection of other L electrons not so directed as to leave the target. This is a considerably greater amount of energy than the total radiation from tungsten at 83 kv (about 0.75 percent). Thus this comparison, and also comparison with other data on line-emission efficiencies,[6] lead to serious doubt about the hypothesis that many of the high-speed secondary electrons are ejected L electrons.

However, some of the secondary electrons must be of this type, and a further test is needed. For this purpose, the magnetic velocity spectrum suggests itself, and the next question is what to look for in it.

The secondary-electron velocity suggested by Lorenz's stem-radiation spectra, at least as a maximum, is that which would occur if all the kinetic energy possessed by a cathode ray as it enters the target is transferred to an L electron, which then loses only enough energy to escape from the atom. Most ejected L electrons, however, should have less kinetic energy than this maximum, for two reasons. First, most of the atoms from which the L electrons are ejected are not at the surface of the target, and there are energy

[6] D. L. Webster, Proc. Nat. Acad. of Sci. **14**, 330 (1928). Data here indicate that when an 80 kv. electron strikes a block of silver, it has a line-emission efficiency of only about 0.1 percent.

losses along the paths of both the primary and secondary electrons. And second, in the act of ejection, the cathode ray should probably not transfer all its energy to the L electrons. It may be possible to eliminate the former of these causes for deficiency of energy, if the target can be made thin enough, but the latter is inherent in the atomic process. Thus even with an infinitely thin target, the energy limit described above might at best be looked for in the velocity spectrum only as a discontinuity in the first derivative of the intensity; and with a thick target, only in the second derivative.

These predictions are somewhat discouraging, but not completely so. For even if the secondary electrons were of uniform velocity, like the primary, the discontinuity in the x-ray spectrum of the stem-radiation would still be only in its first derivative. And uniform velocity means, for the velocity spectrum, not simply a finite discontinuity in some derivative, nor even in the intensity function itself, but in its first integral. In general, the order of the lowest derivative in the stem-radiation spectrum, having a finite discontinuity, should be two units higher than that in the velocity spectrum. Thus the better of the two spectra, as evidence on the question in hand, should be the velocity spectrum, which ought therefore to be explored thoroughly. And regardless of all such hypotheses as are discussed above, such exploration will surely improve our understanding of the process of secondary electron emission.

II. Apparatus and Methods

The apparatus used here was of the well-known type for semicircular focussing of a magnetic spectrum, as described by Robinson,[7] and is illustrated in Figures 1 and 2. The source of the secondary electrons to be

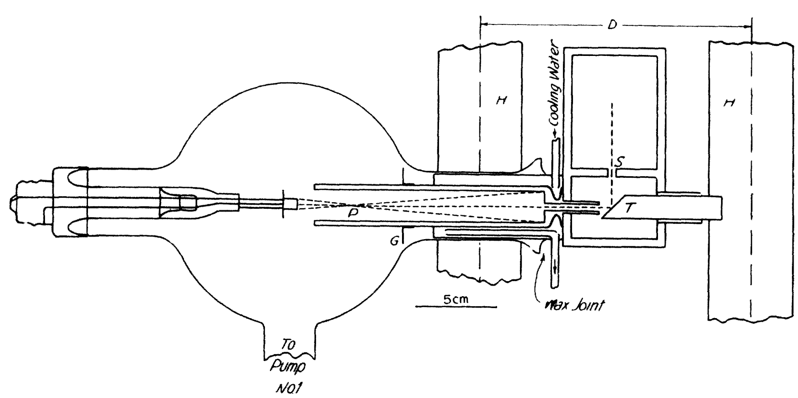


Fig. 1

analyzed into a spectrum is the target, T, shown from two directions in Figs. 1 and 2. The familiar magnetic focussing of the electrons is illustrated in Fig. 2, while Fig. 1 shows how the primary rays came along the lines of the magnetic field, as in Chilinsky's apparatus. Thus they travelled in straight

[7] H. Robinson, Proc. Royal Soc. **A104**, 455 (1923).

lines, from the Coolidge cathode in the glass bulb at the left, to the target *T*. The current producing this field ran in a pair of Helmholtz coils, indicated in Fig. 1 by the broken segments marked *H*. The brass box, in which the electrons made their semicircular paths, communicated with the glass bulb only through the very narrow slit *S*, and both of the chambers needed very good vacuum. Therefore, even though a test showed that the pump leading from the box alone would evacuate the bulb satisfactorily, a pump from the bulb was added as a precaution.

The target was sometimes a solid rod of aluminum as shown here, sometimes a brass rod with copper, silver, or gold soldered to it, and sometimes a brass tube, 7 cm deep, with a bore of 1 cm diameter, covered at the end with aluminum, silver, or gold leaf, to make a thin target. In each case, the primary rays struck the target at 45°, and the secondary rays used left it at the same angle, being thus 90° from the primary. The thicknesses of the thin targets were: Al 0.53×10^{-4} cm, Ag 0.18×10^{-4} cm, Au 0.23×10^{-4} cm.

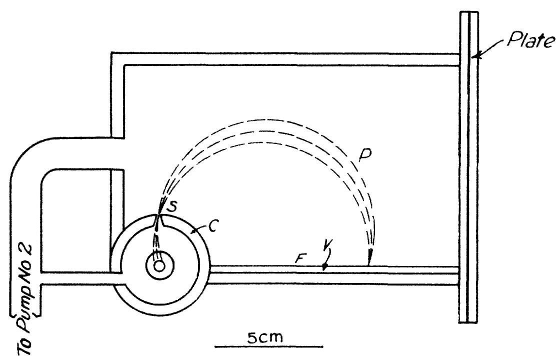


Fig. 2

Some other numerical data were as follows: slit *S*, 1.4 cm by 0.025 cm; diameter of hole through which the cathode rays approached the target, 0.2 cm; fraction of the cathode rays going through this hole, about 5 percent; radius of the Helmholtz coils, 17 cm; center of whole Helmholtz coil system, at the center of an electron path of radius 5 cm; non-uniformity of field (by test coil) not over 0.9 percent from its value at the center, anywhere on a radius of 6 cm.

The voltage applied to the primary cathode rays was obtained by connecting the cathode to the negative line of the D.C. system of the laboratory, and the brass box to the neutral line, which was grounded. It could be held constant to better than 0.3 percent, and the fluctuations due to the primary A.C. were far less than this.

For final use, spectra were photographed at four voltages, 16, 20, 30, and 40 kv, the first two with 1 ma (of which, as noted above, only about 5 percent reached the target), and the last two with 0.6 ma. To insure constancy of voltage and magnetic field in each exposure, the following procedure was adopted. First, the film was inserted, the box closed, and the apparatus pumped to a high vacuum. Second, the current in the Helmholtz coils was set for a value such as to deflect secondary electrons of primary velocity into semicircles of 5 cm radius, and it was watched carefully thereafter. Then the high voltage was turned on, adjusted, and watched by another observer, usually Mr. B. G. Eaton, to whom hearty thanks is due for the care with which he rendered this assistance. Third, the filament was heated gradually, taking about half a minute to heat, so as to avoid voltage disturbances due to slight evolution of gas, and it was maintained at the right temperature for 5 minutes. Finally, the filament current was shut off, then the high voltage, and last the magnetizing current. Thus all the electrons had a primary voltage and deflecting field, each uniform to 0.3 percent, so that no discontinuity in the magnetic spectrum could be blurred by any lack of constancy involving energy changes as great as 1 percent.

Beyond tests for discontinuities, however, this work is purely qualitative although the conditions of exposure and development of the films were kept as constant as possible, to facilitate the comparisons of films. Especial care in this respect was applied to pairs of films, for thick and thin targets of the same metal at the same voltage, which were developed together.

Along with all the ordinary sources of photographic errors, it was unfortunately not found possible to eliminate entirely the effect of stray light from the filament. Tests without high voltage, however, (thus omitting the cathode rays) showed that the most serious fogging by such light occured only in the low-velocity region. In the high-velocity region, say above half the primary ray energy, where most of the secondary electrons appeared, the fog was very light and practically constant. Thus, fortunately, it can be neglected in discontinuity tests or in qualitative comparisons confined to this high-velocity part of the spectrum.

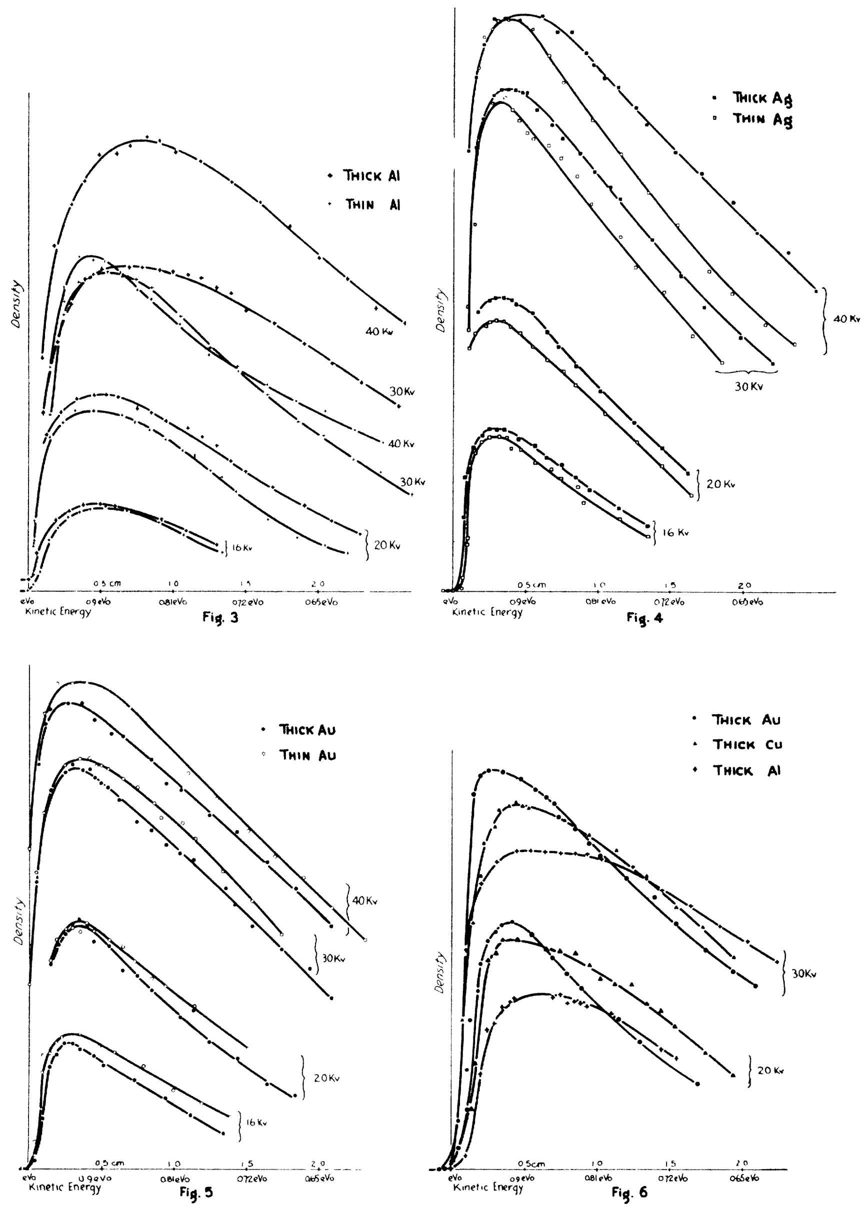
III. Results

Some densitometer graphs, comparing thick and thin targets of Al, Ag, and Au are shown in Figs. 3, 4, an 5 respectively; and some for thick targets only, of Al, Cu, and Au, in Fig. 6.

As will be seen on inspection of these graphs, *all these spectra are continuous.*

With regard to discontinuities in the derivatives of density or number of electrons with respect to velocity, it is evident that *there is apparently a real discontinuity in the first derivative, in every spectrum, at its high velocity end which is always found on measurement to occur at a velocity equal to that of the primary cathode rays. Aside from this point, however, no discontinuities have been found.*

First-derivative discontinuities would of course be much easier to detect than second, of the same relative proportions. Considering now only the thick targets, it has already been noted that we cannot expect to find any evidence of electrons ejected from the inner orbits, except in second-derivative discontinuities. Therefore, so far as we can tell here, such electrons may constitute several percent of the secondary electrons. But if they constituted a majority, it would be a different matter. If, for example, in gold at 20 kv the majority of the secondary electrons were ejected from the M



Figs. 3, 4, 5 and 6

levels, we should expect to find relatively few electrons of energy greater than $(20-4)$ kv, or $0.8eV_0$, and just below this energy we should expect the density to begin to increase rapidly. The facts, however, are totally different from any such prediction, not only in this spectrum, but in all the spectra. We must, therefore, conclude that, although some of the secondary electrons undoubtedly do arise from ejections from the inner orbits, they are a very small minority.

Turning now from discontinuity tests to qualitative information on other matters, still on thick targets, we find for all these elements, Al, Cu, Ag, and Au (as Chilinsky found for Ag up to 20 kv) that most of the high-speed secondary electrons have very high speeds. In terms of kinetic energy the maximum densities in these spectra occur at energy values bearing nearly constant ratios to the primary energy, eV_0. For Al, this optimum energy eV_m is about 0.85 eV_0; for Cu, about 0.90 eV_0; for Ag and Au, each about 0.94 eV_0. The probable errors in these ratios are several percent, of course, especially for Cu, for which relatively few photographs were made.

Below the optimum energy, in every case, the density declines rapidly, reaching half its maximum somewhere around 0.6 or 0.7 eV_0. Part of this decline may result from a decline in the photographic effect per electron, though not if each electron causes development of one grain, as may be possible. These statements on densities give, of course, only a qualitative idea of the laws governing the number of electrons per unit energy interval, but this number must vary in a manner roughly similar to these densities.

Since the conclusions drawn here differ radically from those of Lorenz, a question arises, whether the difference is due to theoretical assumptions in the interpretation of the data, or to some hidden source of experimental error. From the present data on the velocity spectra of the secondary electrons, we may predict roughly the form of the x-ray spectrum of the stem radiation they might excite. Considering only gold, as the element most like Lorenz's tungsten, the outstanding feature is the concentration of the secondary electrons in the general region around 0.9 eV_0, ± 0.1. The x-rays due to such electrons would not be expected to show any very sharp short-wave limit, but the general form of their spectrum would be much like that of the x-rays from the focal spot, except that it would be shifted to wave-lengths about 10 percent longer, and blurred out by ± 10 percent, more or less. Considering the short-wave limit more carefully, what it should show, as noted above, is a finite discontinuity in a derivative of order two units higher than that of the discontinuous derivative in the velocity spectrum. Therefore, since the velocity spectrum has its discontinuity in its first derivative, the x-ray spectrum should start, as measured from its short-wave limit, more or less like the curve $y = x.^3$ In other words, it should have a graph which runs very low near the limit, and curves upward rather sharply at a wave-length somewhat greater. It is, therefore, not inconceivable that this sharp upward curvature might occur in the region where most of the secondary electrons would have their individual short-wave limits, that is, around 10 percent above the true short-wave limit. This is just about the region where Lorenz found a strong upward curvature in each of his spectra, assuming it to be a short-wave limit and assuming the weak radiation of still shorter wave-lengths to be stray rays from the focal spot. Thus it may well be that the only cause for difference between his conclusions and the present lies in these assumptions, and that the data are consistent within the limits of reasonable experimental errors.

Turning now to the thin-target velocity spectra, they prove somewhat disappointing. Differences from the corresponding thick-target spectra are found only in Al and Ag, and there only above 20 kv. However, some recent theoretical work by Bothe,[8] on the stoppage of cathode rays in matter, throws light on this point. In thick targets, only very few cathode rays are stopped far short of their normal range, by large losses of energy; but practically all of them are deflected by nuclear attractions without much energy loss, in very short distances. Thus, at the speeds used here, they have completely lost all sense of direction before they have gone a micron. Qualitative calculations on rather loose assumptions related to those of Bothe, make it quite reasonable to expect many of the cathode rays deflected back out of the metal to have had very short paths within it. Such deflected cathode rays (or rediffused, as Becker would call them) should therefore have two characteristics in common with the secondary electrons observed here: first, that each electron should retain a large fraction of its initial kinetic energy; and second, that a metallic film, whose thickness is small compared to the range of a cathode ray in the metal, should nevertheless be thick enough to give practically the same velocity spectrum as a thick target. The agreement of theory and observation here tends to confirm the view that most of these high-speed secondary electrons are rediffused cathode rays.

With regard to how thin a target must be, to give "single scattering," and really give the velocity spectrum of an infinitely thin target, it seems probable that this requirement of thinness is considerably more severe than that for obtaining a "thin-target" x-ray spectrum. For velocity spectrum work, these spectra show that 0.2 micron gold is "thick" even at 40 kv; likewise 0.2 micron silver and 0.5 micron aluminum are each thick at 20 kv. To consider such films really "thin" from this viewpoint, these voltages must be greatly exceeded.

[8] W. Bothe, Zeits. f. Physik **54,** 161 (1929). Mr. Wagner had not seen Bothe's work, but this application of Bothe's theory tends to confirm the views Mr. Wagner expressed, as to the origin of the secondary electrons, and is therefore a reasonable extension of his paper.