The Energy Distribution of Secondary Electrons from Columbium

L. J. HAWORTH, *Department of Physics, University of Wisconsin*

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Energy distribution curves of secondary electrons from an outgassed columbium target have been obtained with the same apparatus as in similar studies on molybdenum. The results from Cb are qualitatively similar to those from Mo. "Discrete loss" and "fixed energy" groups of secondary electrons are observed at energies which are in most cases slightly less than the corresponding ones in the case of Mo. The number of elastically reflected electrons was also studied as a function of primary energy. The curve shows marked similarity to that obtained from Mo, the peaks again being at somewhat lower energies in the case of Cb. It is shown that the lower values of the energies involved in the various phenomena in the present case are to be expected because of the lower atomic number of Cb and because of its larger lattice constant.

IN a previous investigation[1] it was found that the energy spectrum of secondary electrons from a thoroughly outgassed molybdenum target bombarded with relatively low energy primary electrons exhibited two types of fine structure: (1) three "discrete loss" peaks at energies certain fixed amounts less than that of the primary electrons; (2) three "humps" in the curves at definite secondary energies independent of the primary energy. The efficiency of elastic reflection of the primary electrons as a function of the primary energy was also investigated. The curve plotted from these data also exhibited many peaks and irregularities. Possible interpretations of the results in terms of x-ray and optical levels and of the banded structure of the allowed energies of the conduction electrons were discussed.

In the present paper are described the results of similar experiments using columbium as a target material. This metal was chosen for various reasons. It is next below molybdenum in the periodic table and has the same crystal structure. Furthermore a sample of columbium which had been thoroughly outgassed was kindly made available by Professor H. B. Wahlin who had used it in his thermionic studies of that metal.[2]

A small amount of data obtained some years ago from a target of rhodium is also included.

[1] L. J. Haworth, Phys. Rev. **48**, 88 (1935). An error in this paper has recently been called to the author's attention. The integration limits of curve *a*, Fig. 5, were zero to 6 volts rather than zero to 10 volts as there stated.

[2] H. B. Wahlin and L. O. Sordahl, Phys. Rev. **45**, 886 (1934).

Apparatus and Procedure

The energy distribution of secondary electrons was determined by magnetic analysis using the apparatus already described,[1] with a few minor improvements.

The part of the tube containing the Faraday collector, the amplifying vacuum tube and the grid circuit of the latter were more carefully shielded than before, this time by five grounded layers of copper and tinfoil separated from each other by 1 cm layers of insulating material. The remainder of the apparatus, research tube, leads, rheostats, meters, batteries, etc., was surrounded by single copper and tinfoil shields. All elements of the tube except the Faraday collector were grounded through shielded $4\mu F$ paper condensers. With these precautions it was found that the amplifier was comparitively steady even when severe electrical disturbances were taking place in other parts of the laboratory.

The additional steadiness thus obtained allowed the use of a more sensitive amplifier, which in turn made possible an increase in resolving power by narrowing the analyzer slits.

The Cb furnished by Professor Wahlin was in the form of a long thin ribbon 2.5 mm in width. This was cut into short pieces which were then laid side by side with a slight overlap and spot welded together at the ends. The foil thus formed was laid on the face of the molybdenum target cylinder previously used and protruding edges were bent over and wired.

The outgassing of the columbium in the present research tube extended over some 1500 hours during which period a high vacuum was maintained continuously. As both the target and

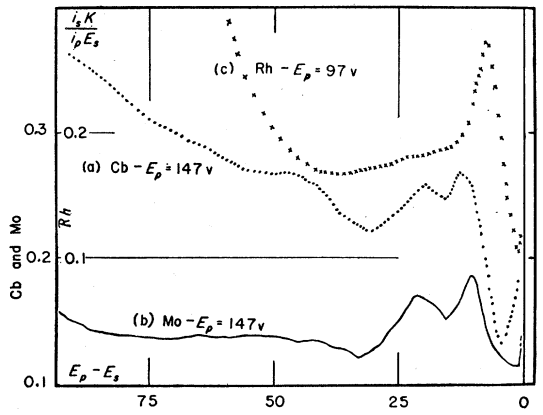

FIG. 1. Discrete loss peaks. Experimental points are indicated on curves *a* and *c*.

the cylinder supporting it had been previously well degassed the process proceeded more rapidly than had new materials been used. At the end of 1000 hours of heating the pressure in the system was 3×10^{-7} mm Hg when the target was hot (1700°K) and 2.5×10^{-8} when it was at room temperature. At this point the ionization gauge unfortunately failed. The McLeod gauge continued, however, to register zero throughout the investigation and it is believed that the vacuum continued to be at least as good as indicated above.

The rhodium, in the form of a thin ribbon filament,[3] was outgassed only 200 hours, after which the filament burned out. Only a very limited amount of data was obtained before this failure.

RESULTS

The number of secondary electrons per primary electron was plotted as a function of secondary energy, proper corrections being made for dispersion by dividing the secondary/primary ratio by the secondary energy.

The distribution curves obtained were qualitatively very similar to those from molybdenum, as to both general form and fine structure. The general shape of the curves is well illustrated by Fig. 2, curves *a*, *b*, *c* of the previous paper.[1]

Discrete loss peaks appeared at energies 12.6, 19.5, and approximately 44 volts less than that of the primary electrons (curve *a*, Fig. 1). The peaks in the case of columbium are somewhat less intense than and a few volts removed from the corresponding ones at 10.6, 22 and 48 volts in the case of molybdenum which are shown in curve *b* for comparison. The peak at 44 volts on the columbium curve is much narrower than is the broad band centering around 48 volts on the molybdenum curve.

Fixed energy groups appear at energies of 9, 21 and 31 volts on an absolute scale (curve *a*, Fig. 2) as compared to 11, 24 and 35 volts in the case of molybdenum (curve *b*). The magnitudes of the irregularities are much less in the case of columbium than in that of molybdenum. This is not necessarily of any great significance as the columbium was probably not as gas free as was the molybdenum and it was observed in both cases that very small amounts of gas were sufficient to entirely mask this effect. It should be mentioned in this connection that no observations were taken at low secondary energies during the later stages of the outgassing. It had been intended to repeat these observations later but an accident to the tube prevented. The 9 volt fixed energy group may have suffered an apparent loss in intensity on account of its position on the curve near the large maximum at 4.5 volts.

The number of elastically reflected secondary electrons is plotted as a function of primary energy for both columbium and molybdenum in Fig. 3. Each curve is marked by a large permanent decrease in the number of elastically reflected electrons as the primary energy is

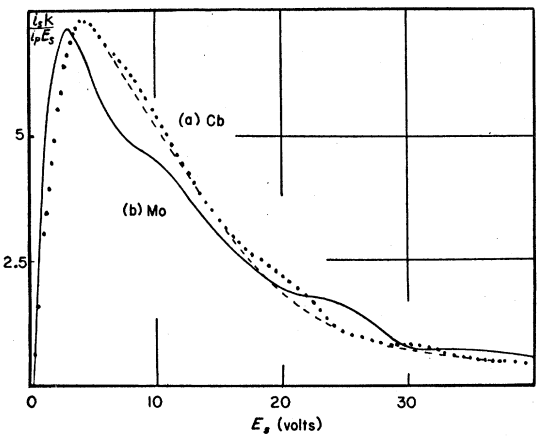

FIG. 2. Low energy secondary electrons showing fixed energy groups. Dots (curve *a*) are experimental points. The dashed line indicates the probable background curve.

[3] The first form of target described in reference 1.

TABLE I. *Energies (in volts) of the various maxima of Fig. 3.*

Cb	2.5	5.0	9.5	12.0	18.5	25.3	32.0	49.0	——	81.5 ——
Mo	3.6	7.6	12.0	——	20.8	28.8	——	50.7	78.5	—— 101

increased beyond a certain point (about 25.5 volts for Cb, 29 volts for Mo), and by a number of maxima and irregularities, principally at low energies. There seems to be a certain correspondence between most of the irregularities of the two curves as indicated by Table I, the peaks occurring at somewhat lower energies in the case of columbium than do the corresponding ones in the case of molybdenum. None of the four peaks[4] which apparently occur for only one metal are very large. The peak at 78.5 for molybdenum was observed in the case of only one specimen out of three well outgassed specimens studied. In fact, it was not the most thoroughly outgassed of the three and was not the one illustrated in Fig. 3. An irregularity similar to the one occurring at 32 volts on the columbium curve was observed at about 34 volts in the case of incompletely outgassed molybdenum but was made to disappear by more thorough heat treatment.

The relative heights of the peaks on the two curves are not the same. In this respect the results from columbium resemble those from an incompletely outgassed molybdenum target more nearly than they do those of curve *b* in Fig. 3.

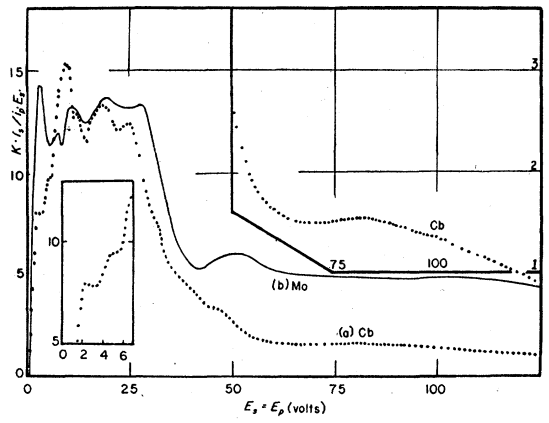

FIG. 3. Elastically reflected (full velocity) secondaries as a function of primary energy.

[4] The words "peak" and "maximum" are here used to describe any irregularities which indicate an abnormally large number of secondaries in the region in question.

Rhodium. The curves obtained from the rhodium specimen were similar in general form to those from the other two metals but the fine structure, in so far as it was investigated, was different. Only one discrete loss peak was observed, that at an energy loss of 7.7 volts. As seen by curve *c*, Fig. 1, it is much greater in magnitude[5] than any of the peaks of the other two metals.

The outgassing of the rhodium was not complete enough to enable one to expect much evidence of fixed energy groups. There was, however, some indication of such a group in the neighborhood of 8 volts.

The efficiency of elastic reflection was not investigated in the case of rhodium.

DISCUSSION

Tentative explanations of some of the results of this type of experiment are possible in terms of the allowed energy states for electrons within a metal.

A discussion of the general form of the distribution curves was given in the previous report[1] and will not be repeated here.

It has been shown[1] that the discrete loss peaks are to be expected from the metallic theory as the excitation processes within the metal should to a large extent be more or less discrete in nature. It is not possible at this time, however, to assign the peaks to any specific excitation processes.

There should be some sort of correlation between the discrete loss peaks and the irregularities of the elastic reflection curve. As the primary energy is increased beyond the values necessary for the excitation processes responsible for the discrete loss peaks there should be sharp decreases in the efficiency of elastic reflection. Any attempt at correlation is, however, complicated by the effects of electron "diffraction." An attempt at a sorting out of these two effects was given for molybdenum. Although a similar analysis is possible in the case of columbium it is not unique and so will not be given.

[5] Note the reduced scale of ordinates for curve *c*. It should be stated that slight changes in apparatus geometry somewhat affect the relative intensities for the various metals in all of the curves of this paper. Such differences, however, probably do not amount to more than a few percent

It has been pointed out that most of the irregularities of curve *a* Fig. 3 occur at lower energies than the corresponding ones of curve *b*. This is to be expected in general, whatever the explanation. As the lattice constant is greater for columbium (3.29A) than for molybdenum (3.14A) the spacing of the allowed and disallowed energy bands will be less in the former than in the latter. Thus energy transfers between zones should involve smaller amounts of energy. For the same reason the energies at which diffraction peaks occur will be less, for it is in reality these zones, or rather their counterparts in momentum space, which are responsible for this phenomenon. Furthermore, the lower atomic number of Cb will cause the energies involved in the excitation of optical and x-ray states to be smaller than in the case of molybdenum.

In the case of molybdenum the sharp decrease in the number of elastically reflected electrons which occurs when the primary energy is increased beyond 29 volts was interpreted as being due to the excitation of the $N_{II, III}$ x-ray states. On the curve for columbium this occurs at an energy approximately 3.5 volts less than the similar decrease on the molybdenum curve. This is approximately the same difference as that which exists between the $N_{II, III}$ term values for the two metals as given by Siegbahn.[6] ($N_{II, III} = 38$ volts for molybdenum, 35.6 volts for Cb.)

No certain connection can be found between the fixed energy groups and either the discrete loss peaks or the irregularities of the elastic reflection curve. It is noticeable, however, that the large maximum at the low energy end of the distribution curves occurs at a higher energy in the case of columbium than in that of molybdenum, which may be connected with the fact that the energy loss involved in the first discrete loss peak is greater in the case of columbium.

The fixed energy groups found at 11 and 33 volts on the molybdenum distribution curves were interpreted as being the result of the banded structure of the allowed energy states above the conduction levels. It was pointed out that their positions were in agreement with certain peaks in the fine structure of x-ray absorption curves which Kronig[7] has explained in this way. Although no x-ray data are available for columbium the corresponding groups at 9 and 32 volts have energies lower by just about the amount that one would expect from a comparison of the lattice constants.

The fixed energy group at 21 volts may arise from a similar cause but it seems more likely that it results from the photoelectric action of soft x-rays emitted on the return (in steps) to the normal state of atoms in which the $N_{II, III}$ levels are excited. Again the difference in the energies involved in the two cases is in the right direction and of approximately the right magnitude to agree with this hypothesis.

The author is indebted to Mr. L. D. P. King for aid in the performance of certain phases of the work.

[6] M. Siegbahn, Zeits. f. Physik **88**, 559 (1934).

[7] R. de L. Kronig, Zeits. f. Physik **75**, 191 (1932).