RADIATION FROM CÆSIUM AND OTHER METALS BOMBARDED BY SLOW ELECTRONS

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ABSTRACT

The absolute intensity and intensity wave-length distribution of the radiation from Cs, Cr, Ni, Mo., and W is measured and found to be similar for all five metals. Control measurements are also made allowing the effect of surface contamination to be estimated. It is found that the radiation from contaminated surfaces is usually much more intense than from clean metals. It is pointed out that the similarity between the radiation from cæsium and other metals makes it probable that the radiation is analogous to the continuous X rays and is not due to the excitation of electron levels characteristic of the metal.

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I. INTRODUCTION

It has been observed in this laboratory that a small metal electrode (Langmuir probe), drawing a heavy electron current in a gas discharge, emits radiation. The properties of this radiation, dependence upon the metal used as electrode, the energy of bombarding electrons, etc., have been set forth in two previous papers.[1]

The principal facts may be summarized as follows: The spectrum of radiation is continuous and of almost constant intensity throughout the visible and ultra-violet. Exceptions are silver and copper which possess intense selective emission bands. The absolute intensity of the radiation for most metals is about the same. For electron energies of 2 or 3 volts the spectrum has a short wave-length limit, the frequency of which is connected with the work function of the metal and the electron energy by the familiar Einstein photo-electric equation. The intensity of the radiation is of the order expected for the "bremsstrahlung" produced by electrons with energies of the order used, which suggests that the radiation is similar in orgin to the continuous X rays.

The present work is a continuation of the studies described in the first two papers in the earlier work. The absolute intensity measurements were few and the results discordant. It was therefore decided to make more extensive absolute measurements and at the same time look for unknown factors, such as surface contamination, which might influence the results.

[1] F. L. Mohler and C. Boeckner, B. S. Jour. Research, vol. 6 (RP297), p. 673, 1931; vol. 7 (RP371), p. 751, 1931.

It was also decided to measure the radiation from several metals not studied previously, namely, Cs, Cr, Mo, and Ni. The radiation from cæsium was considered of particular interest because of the exceptional properties of the metal and because a cæsium electrode surface in a cæsium discharge could be kept very clean.[2]

II. EXPERIMENTAL

1. METHOD

For information concerning the technique, the original papers should be referred to. Some details, however, will be mentioned.

The intensity measurements were made by the usual photographic methods, using an incandescent tungsten strip at various temperatures as a comparison source. An E2 Hilger quartz spectrograph was used to photograph the spectrum of the radiation and quartz fluorite achromats were used to focus the image of the electrodes on the slit.

A low-voltage hot cathode discharge in cæsium vapor was used as a source of electron current to the probe. The discharge tube was placed in a furnace at about 170° C. to maintain the required Cs vapor pressure (several thousandths of a millimeter).

The electrodes were usually in the form of cylinders 2 to 4 mm in diameter. The sides were insulated by glass tubing and the flat polished ends exposed to the discharge.

2. CONTROL MEASUREMENTS

A number of control measurements were made in order to locate possible sources of contamination of the probe surfaces. In the earlier work the probes had been placed in the negative glow of the discharge, near the barium oxide coated platinum cathode. It was suspected, however, that barium or oxygen evaporated from the cathode might contaminate the probe surface. Measurements were therefore made in the negative glow, using a tungsten cathode, and also in the positive column some 15 cm from the cathode.

In most of the work the probes were outgassed at 400° C. and the metal surface cleaned by several hours' bombardment with 100-volt Cs ions. To ascertain the effect of better outgassing and a possibly cleaner surface, a tungsten electrode was used in the form of a wire 0.4 mm in diameter and 1 cm long. The wire could be heated to incandescence and outgassed by current passed through it from insulated supporting leads.

3. MEASUREMENT OF THE CÆSIUM RADIATION

A specially designed tube was required for the measurement of the radiation from a cæsium electrode. A tungsten wire, 2 mm in diameter and several centimeters long, was sealed into the glass wall of a discharge tube, the inner end being flush with the glass wall. The other end projected from the tube and through the walls of the furnace into the air. Upon blowing air against the end of the wire the end in the discharge was cooled sufficiently to condense a bright layer of cæsium upon it. If the electron current to the probe was too large

[2] A cæsium vapor discharge was found to be most suitable as a source of current to the electrodes due to the relative scarcity of lines in its arc spectrum. Scattered light from the discharge is a serious difficulty in the type of work described here.

the cæsium evaporated; if too small it would spread over the surrounding glass wall. A current and voltage could easily be found for which the cæsium just covered the end of the wire. The cæsium could be evaporated and deposited many times during the observations, thus insuring a clean surface. The diameter of the cæsium

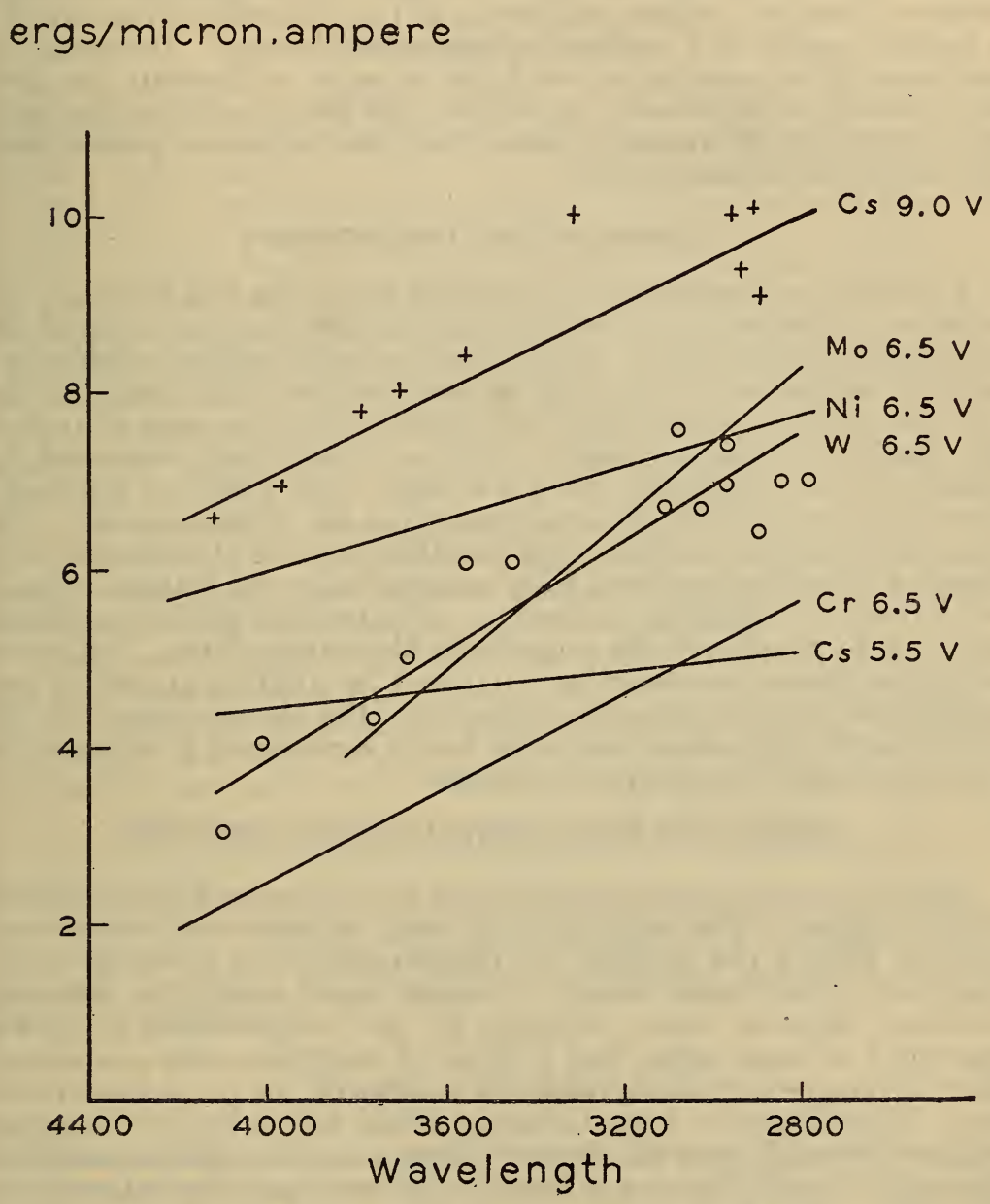

FIGURE 1.—*Absolute intensities of radiation from metals*

Ordinates, intensities in ergs per ampere in a micron wave-length range. "o" tungsten 6.5 volts; "+" cæsium 9 volts.

disk, a knowledge of which was necessary in order to determine the current density, was evaluated from the size of the image on the spectrograms. It may be mentioned that a monatomic adsorbed cæsium layer present on the other metals studied does not, of course, constitute a difficulty in the case of a cæsium electrode.

III. RESULTS

1. ABSOLUTE INTENSITIES

The curves of Figure 1 give the results of the intensity measurements. The intensities are given in ergs in a micron wave-length range emitted by a square centimeter of the electrode surface and for a current density of 1 ampere per square centimeter.[3] The measurements are given together in one figure in order to illustrate the similarity between the metals. It will be seen from the following paragraph that the differences between them are not much greater than the experimental uncertainty.

2. EXPERIMENTAL UNCERTAINTY

A series of measurements on tungsten electrodes will illustrate the influence of various factors on the intensity and the magnitude of the experimental uncertainty. An electrode near the cathode yielded 4.5 ergs per ampere at 3,700 A for electron energies of 6.5 volts; in the positive column, 15 cm from the cathode, 4.1 ergs were obtained; the filament electrode, which could be cleaned and outgassed by heating to incandescence, gave 5.6 ergs. The first two electrodes were outgassed at 400° C. and cleaned by ion bombardment. The agreement is fair and shows that the latter method of outgassing and cleaning is satisfactory and that contamination by material evaporated from the cathode is not serious. Fluctuations in check measurements were usually of the magnitude illustrated above. As causes of the variations there may be mentioned, in addition to surface contamination and photometric difficulties, the uncertainties in the current collecting area of electrodes due to variation in fit between the glass insulators and the metal cylinder.

3. RADIATION FROM CONTAMINATED SURFACES

Before cleaning by ion bombardment the electrodes were sometimes visibly stained. The radiation from such surfaces was usually very intense; after a few seconds ion bombardment the intensity would drop to a much lower value. Changes could usually be detected, however, after an hour's cleaning by ion bombardment.[4] It was suspected in some cases that a layer of tungsten oxide evaporated from the tungsten cathode might be responsible for the intense radiation. Measurements were, therefore, made with a layer of tungsten oxide evaporated upon the electrode from a near-by oxidized tungsten filament. The radiation was found to be ten times more intense than that from a metal, but to have about the same intensity distribution between 4,500 and 2,700 A. Measurements made at low voltage indicated a work function of about 2.4 volts, somewhat higher than that for a metal in cæsium vapor. The surface layer was, however, soluble in water and was probably a compound of cæsium and tungsten oxide formed during evaporation in the presence of cæsium vapor. A grayish white layer of oxide, formed during evaporation in the absence of cæsium, emitted radiation two or three times stronger than the metallic radiation.

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[3] The variation of intensity with angle is supposed to be similar to that of a black body.

[4] Published data on sputtering indicates that the ion current densities used here remove of the order of an atomic layer in a second.

The measurements of the radiation from aluminum previously reported were from a contaminating layer which seems to form upon an aluminum surface in a cæsium discharge. The peculiar minimum in the voltage intensity relation reported in the earlier paper is characteristic of this layer and not of aluminum.

IV. DISCUSSION

The fact that the radiation from cæsium is similar to that from other metals is of some interest in connection with the theory of its origin. One possibility is that the radiation is analogous to the continuous X-ray spectrum and is produced by the deceleration of the bombarding electrons in the fields of the metal atoms. Another suggestion supposes that the primary electron ejects a free electron from the metal and that another free electron then falls into the vacated level with emission of radiation. The latter explanation would predict that, for sufficiently great energy of the bombarding electrons, the spectrum would possess a fixed short wave-length limit, the frequency of which corresponds to the energy spread of the free electron levels. For most metals the width of these levels is of the order of 10 volts and the limit would lie in the far ultra-violet. For cæsium, however, this width, according to most writers,[5] is near 2 volts and the cæsium spectrum should have a high frequency limit in the red or yellow. Since this is not observed one may conclude that the "bremsstrahlung" explanation is probably the correct one.

This view is suggested by the observations of O. W. Richardson and his coworkers [6] that the total intensity of soft X rays produced by 300 to 6,000 volt electrons is very nearly independent of the metal from which the target is made. The extreme variation between 14 metals was less than twofold. This fact is analogous to the similarity of the radiative properties of metals in the low-voltage region described in the present paper, and suggests that the phenomena have a common origin.[7]

The observed intensity may be compared with that predicted by quantum theory for the continuous radiation generated by slow electrons impinging on protons.[8] The radiation emitted in ergs in frequency range $d\nu$ is

$$J(\nu) = g32\,\pi^2 Z^2 e^6\, d\nu / 3\sqrt{3} c^3 m^2 v^2 \qquad (1)$$

The intensity is given in ergs per proton for a current of 1 electron passing through a square centimeter in a second. Z is the charge on the proton; e, m, and v are the charge, mass, and velocity of the electron; g is a numerical factor equal to unity classically, and also in the quantum theory for the case of slow electrons.

It is of interest to compute the intensity radiated by 6-volt electrons, for example, falling on a monatomic layer of protons (0.25×10^{16} on a square centimeter). In the units of Figure 1, one obtains at 3,000 A roughly 80 ergs, about ten times greater than is observed.

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[5] Ig. Tamm, Phys. Rev., vol. 39, p. 170, 1932.

[6] O. W. Richardson and F. S. Robertson, Proc. Roy. Soc., vol. 124, p. 188, 1929.

[7] The similarity is surprising when one considers the extreme difference in the properties of tungsten and cæsium, for example: the atomic volume of cæsium is seven times that of tungsten; the spread of energies of the free electrons in tungsten is perhaps three or four times that of cæsium; tungsten has the highest melting point of the metals, while cæsium was a liquid under the conditions of the measurements.

[8] A. W. Maue, Ann. der Physik, vol. 13, p. 161, 1932.

When it is considered that many layers of charged centers contribute to the radiation in the experimental case of electrons striking a metal, the discrepancy becomes even greater.[9] "Z" was made unity in the computation because the field of the singly charged nucleus was thought to represent more nearly the fields actually encountered by the bombarding electrons.

Leo Neledsky [10] has computed the intensity to be expected when the nucleus is surrounded by its shielding electrons. Using a rough model of such a system of charges, he obtained values much lower than those given by equation (1) and in better agreement with the observed magnitudes. The classical explanation is of course that the external electrons prevent the bombarding electrons from approaching near the nucleus where most of the radiation is emitted.

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[9] The agreement with the theoretical intensity for thick targets reported in an earlier paper was due to the use of the Thomson-Whiddington formula for the depth of penetration of electrons into metals. This relation can not be applied to slow electrons.

[10] Leo Neledsky, Phys. Rev., vol. 39, p. 552, 1932. (Abstract.)