THE PHOTO-ELECTRIC AND THERMIonic PROPERTIES OF IRON

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The photo-electric properties of metals which have undergone a thorough outgassing process by heat treatment have not been extensively studied. DuBridge,\(^1\) Warner\(^2\) and Kazda\(^3\) have studied the photo-electric characteristics of platinum, tungsten and mercury, respectively, taking particular outgassing precautions. An effort is being made in this laboratory to extend the study to other metals. The investigations reported in the present paper have yielded some interesting results for pure iron. Others in this laboratory are at the present time working with molybdenum, tantalum and cobalt.

The present paper is a preliminary report of investigations of the following phenomena:

1. The variation of the photo-electric sensitivity of iron as it undergoes an extended process of outgassing by heat treatment.
2. The effect of crystallographic changes on the photo-electric sensitivity of thoroughly outgassed iron.
3. The effect of a crystallographic change on the thermionic emission from outgassed iron.
4. The variation of the long wave-length limit through the outgassing process.

The apparatus was similar to that used by DuBridge\(^1\) and consisted essentially of a narrow strip of iron suspended inside a nickel receiving cylinder, the whole being enclosed in a Pyrex tube which was connected through a liquid air trap and a mercury cut-off to the pumps. A quartz window, sealed directly on the pyrex tube served to admit the radiactions from a quartz mercury arc. The pressures could be measured by a McLeod gauge or an ionization manometer of the type described by Dushman and Found.\(^4\)

The electrolytic iron, used in this work, was supplied by Professor Watts of the chemical engineering department of the University of Wis-
After being carefully annealed in a vacuum ($10^{-3}$ mm. of Hg), the iron was rolled into strips 0.02 mm. thick, 3 mm. wide and about 10 cm. long. These strips were in some cases cleaned with dehydrated alcohol before being suspended in the form of a loop in the nickel receiving cylinder, but such cleaning produced no essential change in the characteristics.

The photo-electric currents, produced by the radiation from the arc, were measured by a Compton electrometer having a sensitivity of 300 mm. per volt. A resistance of $10^8$ ohms shunted across the quadrants permitted the currents to be measured by the "steady deflection" method.

![Graph](image)

**FIGURE 1**

Interval 1 (0 to 10 hrs.), heated filament at 300°C. Interval 2 (10 to 60 hrs.), baked entire tube at 550°C. Interval 3 (60 to 206 hrs.), gloved filament at 875°C. Drop in sensitivity at C due to supercooling from above 910°C.

**Pressures.**—During the initial stages of outgassing the ionization gauge showed great increases of the pressure in the tube when the filament was heated. These increases in pressure became smaller as the outgassing progressed, and finally no change could be observed when the filament was heated. The final pressure obtained was $1 \times 10^{-8}$ mm. of Hg.

**Variation of Photo-Electric Current with Time of Outgassing.**—The data for figure 1, which shows the effect of heat treatment on the photo-electric sensitivity for one particular specimen, were taken immediately after the heating currents had been cut off. During interval 1 there was a tremendous increase in the photo-electric sensitivity followed by an equally great decrease. No photo-currents were measured during interval 2.
while the entire tube was being baked at 550°C. However, the photo-electric sensitivity was much less after this baking interval. (Point $A$, Fig. 1.) The photo-electric current increased in rather abrupt steps during interval 3, finally reaching a value which did not change with additional heat treatment at the same temperature. A probable reason for these abrupt changes will be pointed out later. As outgassing progressed the photo-electric sensitivity changed less rapidly with time, while standing cold, until finally a thoroughly outgassed specimen showed no fatigue for 12 hours after heat treatment. The time required for outgassing varied a great deal for the different specimens. However, the general behavior was in every case the same.

After this condition of stability had been attained, it was found that the magnitude of the photo-electric current depended on the rate of cooling the filament. An iron surface having a photo-electric sensitivity near the value of $C$ (Fig. 1) was produced when the filament was suddenly cooled from above 910°C. to room temperature. To again produce photo-currents near the value of $B$ (Fig. 1) it was only necessary to cool the filament more slowly to room temperature or to cool it more slowly to below 910°C. and then suddenly to room temperature. Surfaces having either of these sensitivities could be obtained even after more than 100 hours of additional heat treatment. For reasons which will be pointed out later, it may be said that this decrease in photo-electric sensitivity which occurred when the filament was cooled suddenly from above 910°C. was due to the retention of a part of the $\gamma$ iron.

Variation of Photo-Electric Sensitivity with Temperature.—The data for figure 2 were obtained while the filament was hot and after it had been thoroughly outgassed by more than 150 hours of heat treatment. The curve shows the variation of the photo-sensitivity with the temperature at which observations were made. As it was impossible to use the optical pyrometer for measuring temperatures below 875°C., the photo-current has been plotted as a function of the heating current through the filament. The temperatures corresponding to three heating currents have been indicated in the figure. These temperatures were located by comparing a resistance-heating current curve with the resistance-temperature curve obtained by Burgess and Kellberg. The resistance of the leads from the seals to the filament was so small compared with the resistance of the filament that, in addition to the change in slope at 768°C. and 910°C., it was possible to obtain the small "resistance-hysteresis" effect near the transition from $\beta$ to $\gamma$ iron. The optical pyrometer was also used to check the point at 910°C.

Curves 3 and 4 were taken while the pressure was $1 \times 10^{-8}$ mm. of Hg; curves 1 and 2 were taken after the pressure had been increased to $5 \times 10^{-8}$ mm. of Hg. The increase in pressure was produced by heating
the glass parts of the tube with a flame after the pumps had been disconnected from the system by a mercury cut-off. The arrows on the curves indicate increasing and decreasing heating currents.

Many such curves have been obtained using two different specimens and, although the absolute magnitude of the change varied slightly, in no case did the curves fail to show the change indicated by the curves in figure 2. Due to the large thermionic emission, measurements of the photo-electric currents at higher temperatures have up to the present time not been successful.

Thermionic Current.—If the thermionic current is plotted as a function of the heating current (temperature) as is done in figure 3, there is, at a heating current corresponding to 910°C., a departure from the ordinary thermionic-temperature curve. The temperature indicated in the figure is the average and therefore due to the end losses, parts of the filament reached the transition point at a slightly lower heating current. Several such curves have been obtained and each showed the change near 910°C.

Long Wave-Length Limit.—The long wave limit for thoroughly outgassed iron was found to be between 2580 Å and 2652 Å. These limits were determined by the use of absorption cells in the path of the incident light. Photographs taken with a quartz spectrograph showed that the mercury line λ 2652 Å was transmitted quite strongly by a solution which absorbed all the photo-electrically effective energy. The energy transmitted by a solution which cut off sharply just below the mercury line λ 2580 Å produced a photo-current of 0.5 mm. The electrometer sensitivity was increased eleven-fold for these observations.

If these limits are substituted in Einstein's photo-electric equation, the work-function for thoroughly outgassed iron is found to be 4.72 ± 0.07 volts.

No change from the above value of the photo-electric threshold could be detected for iron which had been cooled suddenly from above 910°C. In view of the fact (pointed out in connection with the discussion of Fig. 1) that only a part of the γ iron was retained in such a filament, it would hardly be expected that the threshold would be different from that of α or β iron, since the latter forms probably have, if anything, a smaller work function than the γ form. Attempts at determining the threshold for iron at temperatures above the transition points have, so far, not been successful.

The long wave limit was measured several times as the outgassing progressed. The limit increased to a value above 3000 Å at the end of five hours' heat treatment (see Fig. 1). Accompanying the decrease in the photo-electric sensitivity which was caused by further heat treatment, a corresponding decrease in the long wave limit was observed, a value as low as 2400 Å having been obtained after the tube had been baked at 550°C. (Point A, Fig. 1.)
It has been pointed out above that the threshold increased from 2400 Å to between 2580 and 2652 Å during the heating interval, 60 to 120 hours (Fig. 1). It is therefore believed that the abrupt increases in the photo-electric sensitivity in this interval occur as new lines in the irradiating light become effective.

Welch⁶ has recently reported a long wave limit of 3150 Å for iron, the surface of which was filed in a vacuum, but the specimen was not thoroughly heat treated. Apparently Welch's filing process gave him a surface having approximately the same characteristics as are produced by a few hours' heating in a vacuum (see maximum point, Fig. 1, where threshold was above 3000 Å). Furthermore, Welch reports a photo-electric fatigue, which was in no case observed with thoroughly outgassed specimens during the present work. His results, therefore, cannot be taken as characteristic of gas-free metals.

Discussion of Results.—It is seen from figure 2 that the variation in the photo-electric current with temperature is quite complex. Between about 475°C. and 768°C. there is a decrease in the sensitivity which is perhaps a pure temperature effect analogous to the increase obtained for platinum by DuBridge.¹ At 768°C. a new factor enters and the sensitivity either remains constant or increases slightly up to 910°C. This change is obviously closely associated with the transition, at 768°C., from α to β iron,
which involves a slight increase in the edge of the unit cube but no change in crystal form. Near 910°C., where the crystal structure changes from the body centered cubic to the face centered cubic type, there is an abrupt decrease in the photo-electric sensitivity. Beyond this transition from \( \beta \) to \( \gamma \) iron, there is an increase in the sensitivity. A radical change at the \( \beta \) to \( \gamma \) transition is consistent with the observation of Burgess and Scott\(^7\) upon the thermoelectric power of iron. They found that at the \( \alpha \) to \( \beta \) transition point there is only a change in the slope of the thermoelectric power curve, while there is a marked drop in the curve at the \( \beta \) to \( \gamma \) transition.

The thermionic curve (Fig. 3) is an interesting extension of the work of Goetz\(^8\) who studied the thermionic properties of iron from 1100°C. through the melting point. He concludes that there is a decrease in the \( N \) of the Richardson equation without a change in the \( \Phi \), at the transition from \( \gamma \) to \( \delta \) iron. The present apparatus was not designed for thermionic measurements and this, combined with temperature uncertainties, makes it impossible to say whether the change near 910°C. corresponds to a decrease in the \( N \) or an increase in the \( \Phi \) of the Richardson equation. The work will be extended to clear this point. If, however, the change at 910°C. corresponds to a decrease in \( N \), then a comparison with Goetz's work shows that \( N \) decreases at both the transitions, \( \beta \) to \( \gamma \) and \( \gamma \) to \( \delta \), whereas the crystallographic changes are exactly opposite in the two cases.

While there can be no doubt that the changes in the photo-electric sensitivity with temperature and the break in the thermionic curve are associated with the known transitions in the iron, it is possible to take the point of view that these are indirect rather than direct results of such transitions. It is possible to take the position that the specimen was at no time free from gas and to assume that there is a characteristic equilibrium value of the gas content of the surface which is a function of the temperature and also of the crystal structure resulting in the observed variations of the photo-electric sensitivity. The curves of figure 2, which were taken at greatly increased pressures, are evidence against this point of view because they show that the above hypothetical equilibrium gas
layer is not altered by a five-hundred fold change in the surrounding pressure. Further evidence for believing that a condition characteristic of the metal itself has been reached is furnished by the fact that the photoelectric sensitivity of an outgassed specimen remains constant for twelve hours after heat treatment. The work of Davisson and Germer on electron reflection from nickel is also against such a point of view. They found that it takes several hours for the characteristic reflection to be obscured by the accumulation of gas on the surface.

The work is being continued and a more complete report will be published soon.

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EVIDENCE FOR THE CONTINUOUS CREATION OF THE COMMON ELEMENTS OUT OF POSITIVE AND NEGATIVE ELECTRONS

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The evidence obtained from the study of cosmic rays that the more stable and more abundant elements like helium (abundant in the heavens), oxygen, silicon and iron, are being formed at the present time out of the primordial positive and negative electrons, the former of which is the nucleus of the hydrogen atom, may be briefly summarized as follows:

First.—The pilot-balloon experiments of Millikan and Bowen, in which they sent up recording electroscopes 0.92 of the way to the top of the atmosphere and in which the absorption coefficient of the cosmic rays at, or near, the top of the atmosphere came out of the same order of magnitude as that found near sea-level, show conclusively that these rays consist of a definite and distinct region of spectral frequencies, or oscillations, a hundred times more rapid than those produced by the most powerful sub-atomic changes heretofore known, namely, those accompanying radio-