SECONDARY ELECTRON EMISSION OF NICKEL AT THE CURIE POINT*

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1. Introduction

The phenomenon of the secondary electron emission from metal faces has been studied by a large number of workers in recent years. An excellent summary of these studies is given by Warnecke (1936).

The general disposition of the variations of the secondary electron coefficient at increasing applied potentials may now be taken to be definitely established. Rao (1930) has shown that as the applied potential is increased from zero, the ratio of the secondary to the primary current increases rapidly, attains a maximum value in the neighbourhood of 3 volts and then decreases gradually up to about 20 volts. The value then rises steadily, attaining a maximum at a potential of about 500 volts and thereafter decreases slowly. These results were obtained with polycrystalline nickel; but the same general conclusions have been found to hold good in the case of other metals. The absolute value of the secondary electron coefficient at any applied potential and the potential at which the coefficient attains a maximum value are found to vary from metal to metal.

The similarity of the phenomenon of soft X-ray excitation and secondary electron emission led Richardson (1930) to postulate a mechanism for the observed velocity distribution of the secondary electrons. Rudberg (1930) had previously discovered the presence of three groups of electrons in the secondary emission. The first group in accordance with these conclusions contains electrons which return with the same velocity as the primary. Those electrons which undergo inelastic collisions with the orbital and structure electrons and are hence returned with some loss of energy constitute the second group. Finally there is the third group of electrons which include the slow secondary electrons.

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*A preliminary account of this work was communicated to the Proceedings of the Indian Science Congress Session held in January 1938. The publication of the detailed report has unfortunately been delayed till now.
Richardson (1930) suggested that the high-energy group of electrons resulted from inelastic encounters of the incident electrons with the structure electrons which attained states of higher energy. On their return to the ground state, soft X-rays and low-energy secondary electrons were ejected. Richardson's picture explained a complicated process and accounted for the remarkable similarity in property between soft X-ray excitation and secondary electron emission.

Studies on the efficiency of secondary electron emission by Rao (1933) established the conclusion that the first group of secondary electrons is large at applied potentials below 10 volts but becomes small at higher potentials. The efficiency of the second and third groups is small at low primary potentials and increases rapidly as the potential is raised.

It is necessary to set forth these considerations at some length to appreciate the experimental work of Tartakowsky and Kudrjawzewa (1932), who found that the secondary electron coefficient showed a sudden decrease in value at the Curie point in the case of nickel. Their apparatus consisted of a nickel plate which was heated by a tungsten filament fixed on one side. The primary electrons were incident on the other side. Part of the secondary emission fell into a Faraday chamber and was measured with an electrometer.

Treloar and Landon (1938) have pointed out the drawbacks in the arrangement employed by Tartakowsky and Kudrjawzewa (1932). No precise physical significance can be attached to the results of the latter workers unless the following conditions were satisfied over the temperature range adopted: (1) constancy of angular distribution of the emitted electrons; (2) constancy of energy distribution of the emitted secondaries; (3) constancy of potentials on the glass walls; (4) absence of stray magnetic fields due to the current in the filament used to heat the target. It is obvious that these conditions were not satisfied in their experiments. They found that at an applied potential of 30 volts, the secondary electron current increased when the temperature of nickel was raised from 150° to 350° C. An abrupt fall was obtained at the Curie temperature (358° C.) and thereafter there was a continuous increase. Working with a copper target, the secondary emission was found to increase linearly with temperature. Even this conclusion is at variance with the results of Krefft (1928) who found that the secondary emission coefficient of tungsten was constant in the range from 20° to 1450° C.

Hayakawa (1933) has reported similar observations with iron, cobalt and nickel. In fact he has studied the transformations of metals by secondary
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electron emission. His method consisted in collecting all the secondary electrons emitted and the electrical connections adopted were similar to those of Rao (1930). Treloar and Landon (1938) have drawn attention to the existence of several discrepancies in the results of Hayakawa. The secondary coefficient showed large variations at temperatures corresponding to the Curie point in the case of nickel and to transformation points in the cases of cobalt and iron. Hayakawa interpreted his results in the light of Richardson's theory of structure electrons.

Rao (1937) studied the excitation of soft X-rays and the emission of photoelectrons from nickel at temperatures in the neighbourhood of the critical point of nickel. His results showed no abrupt or anomalous variations at the Curie temperature. He drew specific attention to the inherent difficulties present in the conclusions of Hayakawa (1933) and Tartakowsky and Kudrjawzewa (1932).

Treloar and Landon (1938) investigated the secondary emission from nickel, cobalt and iron. They obtained no sudden changes at the transformation or Curie points. In the case of nickel, they observed a slight and gradual decrease of the secondary emission coefficient when the temperature of the metal target was reduced from 525° to 110° C. They attribute this change to the probable adsorption of gas by the metal surface.

The following experiments were undertaken with a view to investigate the secondary emission from nickel with great care. The heating method adopted was efficient and special investigations were carried out to study the influence of imposed magnetic fields on the secondary emission coefficient. The results show that the secondary coefficient is constant to within 1% in the range 30°-470° C.

2. Experiment

It was felt that a real test should be made with the target thoroughly degassed since internal changes at the Curie point may result in the alteration of the gas content of nickel, which factor by itself may produce several changes in the observed secondary emission.

The experimental method adopted was similar to that of Rao. The tube was made of pyrex (by the Scientific Instrument Co., Allahabad) and is illustrated in Fig. 1. All the metal parts except the filaments were made of thin sheet silver. $F_1$ is the filament of tungsten which gives the primary beam of electrons. $A$ is a shield outside the filament with an aperture of diameter 7 mm. The part $B$ is the electron gun which gives a beam of electrons, the diameter of the beam being 3.5 mm. The primary beam
falls on the target T of pure nickel fixed on the closed end of a hollow metal cylinder C. To facilitate degassing the cylinder and the target, a filament $F_2$ is arranged within the cylinder. The secondary electrons are collected by a shield D outside the cylinder. All the joints and seals were made with tight fitting brass caps and small quantities of hard sealing wax.

During working conditions the pressure inside the tube was reduced to some value less than $10^{-6}$ mm. The vacuum consisted of a Cenco hyvac pump and a three-stage mercury diffusion pump. Two traps, one of which contained coconut charcoal, were cooled with a mixture of carbon dioxide snow and ether. The pressure inside was measured with a Macleod gauge.

The electrical connections adopted are shown in Fig. 2. The heating currents for the filaments $F_1$ and $F_2$ were supplied by storage batteries. The
primary and secondary currents were measured with galvanometers $G_1$ and $G_2$. The required potentials for bombardment were taken from a high tension battery of Dagenite 10-volt accumulators.

The shield $A$ around the filament $F_1$ was usually maintained at 50 V higher than the canal $B$ and the target. A fairly strong electron beam was thus obtained even at moderate potentials.

An additional positive potential of 4 V on the shield with respect to the target was enough to prevent any reflection or emission of electrons from the shield. The electrons reflected back directly through the opening of the shield $C$ will be lost. But since the solid angle subtended by the opening at the centre of the target is small, the decrease will be small. Also in comparative measurements, this decrease will have no influence.

The heating of tube was effected by enclosing the tube in an electric heater containing a suitable number of turns of (S.W.G. No. 22) nichrome wire. The temperature of the target was measured with the aid of a thermoelectric thermocouple, consisting of a wire of pure platinum and another wire of an alloy of platinum and 10% rhodium. This standard thermocouple has been calibrated by the National Physical Laboratory and from the observed electromotive force of the couple, the temperature may be found.

The metal parts were degassed thoroughly by raising the tube to about 500°C. inside the electric heater. The cylinder and the target were simultaneously degassed by heating them to bright red heat by electronic bombardment. Much of the success of the experiment depends on the state of the metal surface and hence special precautions were taken to degass the target completely.

The measurements of the primary and secondary currents were made both when the temperature of the target was increased and when it was gradually decreased.

The target was raised to high temperatures by sending a suitable current in the filament $F_2$ (Fig. 2). A blank experiment was conducted showing the temperatures reached by the target for different currents in $F_2$. This enabled one to raise the target to any desired order of temperature, the correct temperature being found in each case by the thermocouple.

An accurate estimation of the applied potential to which the electrons arising out of the filament $F_1$ are subjected is a matter of some difficulty on account of the uncertain values of the corrections to be applied. These corrections are (1) correction for the initial emission velocity of the electrons
which is about $\pm \frac{1}{4}$ volt at the temperature of the filament, (2) correction for the drop in potential along the filament which works to about $+1.5$ volts and (3) correction for the contact difference of potential between the hot cathode and the nickel target. The last correction is not capable of being correctly estimated. But in this investigation, we are not concerned with the absolute value of the applied potential. What concerns us is the conclusion that increasing the temperature of the target will not modify the total correction to any significant degree.

3. Results

Rao (1930) has obtained evidence to show that the ratio $i_s/i_p$ varies with $i_p$ as the primary current is increased from 0.2–5 microamperes. This variation is nearly 5% and it is necessary to work with a constant primary current if any consistency is to be expected in the observed value of $i_s/i_p$. This point seems to have been lost sight of by a large number of workers in the field of secondary emission.

(a) Total secondary electron curve.—Fig. 3 shows the graph between the ratio of the secondary current ($i_s$) to the primary current ($i_p$) and the applied potential.

![Fig. 3](image)

(a) Warnecke (1936); (b) Petry (1925); (c) Author; (d) Rao (1930).

The results obtained by other investigators in the same region are also given in the same figure. It will be observed that while the absolute values differ from those of other workers, the general nature of the alteration with applied potential remains the same in all cases. The values obtained here lie between those of Petry and Rao.

(b) Secondary emission at different temperatures of the target.—Fig. 4 shows the values of $i_s/i_p$ at temperatures between $30^\circ$ and $500^\circ$ at applied potentials of 66, 88 and 115 volts. Measurements were made both at
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increasing and at decreasing temperatures of the target. It is found that in each case, the value of $i_s/i_p$ is constant to within 1%.

![Graph showing temperature versus $i_s/i_p$ ratio](image)

Hayakawa (1933) found that at an applied potential of 71 volts, the secondary electron emission (he does not state what exactly this term means) rose from about 0.48 at 270° to about 0.6 at 365° (the Curie point) and thereafter to 0.75 at 420°. Similar changes were observed at an applied potential of 87 volts.

Tartakowsky and Kudrjawzewa (1932) found that at an applied potential of about 30 volts, the secondary emission showed a continued increase when the temperature of the metal was raised from 150°–350° C. An abrupt fall occurred at the Curie point (358° C.) and thereafter there was a rapid rise till 445° C. was reached.

Treloar and Landon (1938) found that in the range 100°–525° and at applied potentials of 30, 40, 50, 70 and 100 volts, the secondary emission coefficient showed a slight and gradual decrease as the temperature was raised. They attribute this decrease to the possible adsorption of gas by the metal surface when it was gradually cooled.

The present investigation shows that the coefficient is constant to within 1% in the temperature range 30°–500° C.

(c) Influence of stray magnetic fields.—A careful examination was made of the influence of stray magnetic fields on the value of the secondary electron emission coefficient in any setting. The magnetic field was produced by keeping near the experimental pyrex tube, one or more large bar magnets. The currents read in the primary and secondary galvanometers did not show
any variation. It may be safely concluded that stray magnetic fields could in no way influence the value of the secondary coefficient.

Greater interest perhaps attaches to experiments conducted with the filament taking the position shown in Figs. 5a and 5b. In the first case, there were six turns of tungsten wire, each turn having a diameter of about 4 mm. An approximate calculation showed that the intensity of the magnetic field on the axis of the coil and in the region occupied by the nickel target was of the order 5 gauss. In the second position of the filament, the magnetic field at the same place acts parallel to the axis of the coil and has an intensity which is nearly half this value. But in both the cases the secondary emission had the same coefficient showing that variations of the magnetic field of this order had no effect.

4. Discussion

It appears to the present writer that there is a fundamental theoretical difficulty in the conclusions of Hayakawa (1933). He finds an opposite variation of the secondary electron current above and below a critical voltage, which in the case of nickel is 38 volts. When the incident electrons are accelerated at a potential less than 38 volts, the parts of the secondary electron curve just above and below the point make an angle between 90° and 180° on the side of the temperature axis. But at applied potentials above 38° this angle becomes greater than 180°.

Hayakawa postulates that at applied potentials less than the critical value, only the free electrons are emitted as the secondary electrons. But when the applied potential is greater than the critical value, the ‘structure electrons’ (whose potential energy is larger than that of the free electrons) are involved in inelastic collisions and they are hence expelled as secondary electrons. Hence one would expect an additional secondary emission current as soon as the applied potential exceeds the critical value, but not any kind of opposite variation of the electron current above and below the critical voltage. Further if his reasoning is true, no sudden variation of the secondary emission would be observed at applied potentials less than 38 volts. The reasoning of Hayakawa will not explain the variation at the critical temperature.
Fig. 5 is inverted. Correct position is—

Fig. 5
A theory of secondary emission has recently been suggested by Woolridge (1939a). The production of secondary emission by the interaction of primary electrons with the valence electrons of a metal target was treated by him from the point of view of quantum mechanics. He has developed a method of calculating approximately the variation of the secondary coefficient with applied potential. His expression involves among other factors, the lattice spacing, the mean Fermi energy of the metal and the work function. None of these quantities may be said to vary abruptly at the Curie temperature. Woolridge has verified his deductions with the experimental results of Bruining and de Boer (1938) and of his own investigations on cobalt and nickel (Woolridge, 1939b). There seems to be theoretical justification for the conclusion that the secondary coefficient does not show any sudden change at the Curie temperature.

These considerations receive considerable weight from the experimental work of Rao (1930) to which attention has already been drawn. No anomalies were observed by him in the photoelectric and soft X-ray excitation curves at the Curie temperature. Richardson (1930) has shown that the second group of electrons returned with an energy just lower than the energy of the primary electrons is responsible for the emission of low energy electrons and excitation of soft X-rays. A change in the number of the former at the Curie temperature should be accompanied (most likely) by a change in the latter case.

Attention has already been drawn to the observation of Tartakowsky and Kudrjawzewa (1932) to the steady increase in the secondary coefficient of copper as its temperature was increased from 260°–390°. The secondary emission in arbitrary units rose from 46·5 to 54 in this range. This seems most improbable in the light of the foregoing discussion. Krefft (1928) who worked with tungsten found no change in the secondary coefficient when the temperature was raised to about 1450° C.

5. Summary

A study of the secondary electron emission from nickel has been made at different temperatures ranging from 30°–470° C. at certain definite applied potentials. No sudden alteration in the secondary electron current was observed at the Curie point (358° C.). These results are at variance with those of Tartakowsky and Kudrjawzewa and of Hayakawa. Attention is drawn to the investigations of Rao wherein no abrupt variations were obtained in the photoelectric emission and soft X-ray excitation curves of nickel at the Curie point. It is difficult to understand how in such closely connected phenomena, anomalies exist in one class and not in the other.
Support from this point of view is adduced for the conclusions of this investigation.

I take this opportunity of expressing my grateful thanks to Dr. S. Ramachandra Rao for his interest in the work.

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