The Production of Characteristic X-Rays by Deuteron Bombardment

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It is shown by a photographic method that for deuterons of 10 Mev, characteristic K radiation is emitted from targets of atomic number 38 or less. Because of absorption, the intensity appears to have a maximum for elements of atomic number about 28. Similarly, L radiation is observed for the heavier elements with a maximum in the neighborhood of atomic number 64. For a copper target the yield of x-rays is observed as a function of the exciting energy. The results are compared with the theoretical calculations of Henneberg.

The possibility of producing x-rays by the bombardment of targets with heavy particles was demonstrated as early as 1913 by Chadwick[1] and by Rutherford and Richardson.[2] They employed the alpha-particles from radium emanation. Several later investigations have been made with alpha-particles[3] from natural radioactive sources and with protons[4] whose energies were as high as 1.76 Mev. In these investigations the x-rays have been detected by sensitive ionization chambers or Geiger counters, and the nature of the x-rays revealed by studying their absorption in aluminum. A theoretical treatment of the problem, leading to an expression for the distribution of the x-ray energy with changing atomic number of the target and with the incident energy of the particle has been presented by Henneberg.[5]

Experimental

In observing photographically in a magnetic field the disintegration particles resulting from deuteron bombardment in the cyclotron, a prolific yield of undeflected radiation is found for certain elements. The radiation from the target is collimated by a slit and then dispersed by the strong magnetic field of the cyclotron provided with an auxiliary magnetic shunt. The target is usually a thin strip of material about one-half mm wide and 0.025 mm thick and is mounted at an angle of 45 degrees with the deuteron beam. The radiation is observed at an angle of 90 degrees with the beam, whose dimensions are such that the source of x-rays is a vertical line about five mm long parallel to the vertical slit. The photographic plate was mounted in a carriage at any desired distance from the slit. The x-rays together with any gamma-radiation thus appear in the undeflected position on the photographic plate as shown in Fig. 1.

The energy of the bombarding deuterons was usually about 10 Mev, having a range in air of about 66 cm. For the lighter elements the thin targets had a stopping power of not over 10 cm of air so that the energy of the deuterons was only slightly reduced and the shorter wavelength x-rays were not absorbed appreciably.

Observations were made of the yield of x-rays from about 35 elements distributed throughout the whole periodic table. For those elements not available in thin foils, a finely powdered form of the material was made to adhere to a supporting fiber of one-half-mil aluminum foil. Reproductions of certain of the plates at a distance of six cm from the slit, for a bombarding beam of one microampere for one minute, are shown in Fig. 1. The relative production of x-rays is estimated from the comparative blackening of the photographic plates for identical exposures.

For a particular element such as copper, an attempt was made to determine the yield of x-rays as a function of the bombarding energy. The deuterons were allowed to pass through aluminum foils of various thicknesses before impinging on the target. Experiments were also made to show the quality of the x-rays, that is, that they are the characteristic radiation of the target element.

[1] J. Chadwick, Phil. Mag. **25**, 193 (1913).
[2] E. Rutherford and H. Richardson, Phil. Mag. **25**, 722 (1913).
[3] W. Bothe and H. Franz, Zeits. f. Physik 52, 466 (1928); C. Gersten and W. Reuse, Physik. Zeits. **34**, 478 (1933).
[4] M. Livingston, F. Genevese and E. Konopinski, Phys. Rev. **51**, 835 (1937).
[5] W. Henneberg, Zeits. f. Physik **86**, 592 (1933).

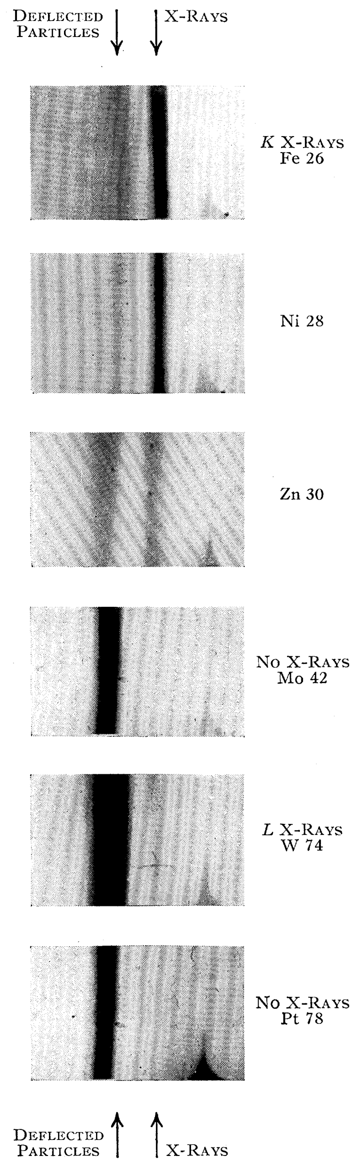

FIG. 1. Photograph showing the characteristic x-rays and deflected particles for certain elements.

Results

For the incident energy of 10 Mev, characteristic K radiation is found for elements of atomic number 38 or less. The estimated relative yields are shown in Fig. 2. Between atomic numbers 52 and 78 the L series x-rays are found but much less abundant than the K radiation for the lighter elements. The maximum for the K radiation occurs for elements of atomic number around 28 and for the L radiation

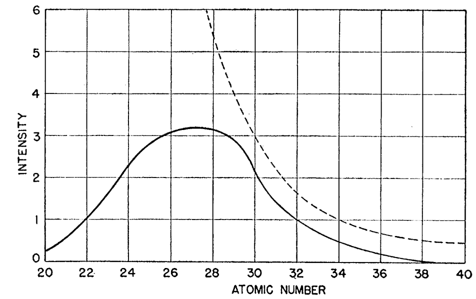

FIG. 2. Relative yield of K radiation from various elements for 10-Mev deuterons (heavy line); theoretical values adjusted at $Z=34$ (dotted line).

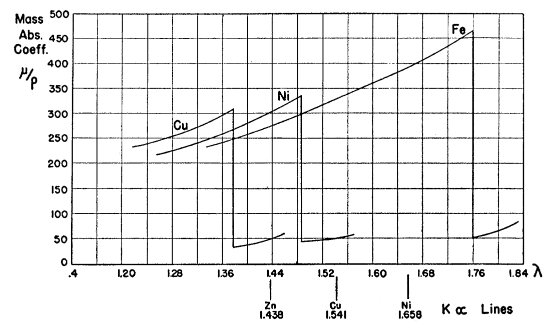

FIG. 3. Wave-lengths of K-emission lines and absorption edges for certain elements.

around atomic number 64. As the energy of the incident deuterons is decreased it is found that the x-rays from a copper target are still observable until the energy approaches 4.5 Mev, or about 17 cm air range.

To make sure that the radiations from a particular element such as copper consist solely of the K x-rays of that element, and are neither continuous nor x-rays emitted subsequent to such a process as K-electron capture by the nucleus, the following experiment was performed for both copper and zinc. The wave-length of

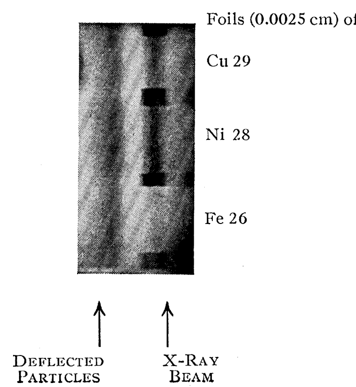

FIG. 4. Photograph showing absorption of x-rays from copper in one-mil foils of copper, nickel and iron.

the copper K alpha radiation is 1.541A. If K-electron capture had occurred in the nucleus then the subsequent x-ray emission would be the K series of zinc whose alpha-lines have a wave-length of 1.438A. The critical K-absorption edges of the elements in this part of the periodic table are shown in Fig. 3. Thus copper K alpha radiation would be strongly absorbed in iron and only slightly absorbed in nickel and copper, while zinc K radiation would be largely absorbed in nickel and iron and scarcely absorbed in copper. By covering the photographic plate with equi-thick strips (0.025 mm) of the three metals a result as shown in Fig. 4 was observed. It is apparent that the iron foil almost completely absorbs the radiation while the copper and nickel only reduce it slightly, as would be the case for copper radiation. Continuous radiation would be absorbed almost equally by the three foils. The radiation from a zinc target was almost completely absorbed by both nickel and iron and only slightly reduced by copper as would be the case for zinc K radiation.

Discussion

If one assumes an elastic impact between the deuteron and the electron, the conservation of momenta and energy expressions indicate an expected excitation energy for each element. For an incident velocity V of the heavy particle of mass M against an electron of mass m at rest, the electron would recoil with a velocity v equal to V plus V' where V' is the final velocity of the heavy particle. Since the mass of the deuteron is relatively so large, V' differs but slightly from V hence v is approximately $2V$. The energy given to the electron is therefore $4m/M$ times the incident energy of the deuteron. Conversely, the critical incident energy expected to excite the K radiation would be $M/4m$ times the well-known critical electron potentials from x-ray spectroscopy. For copper, electrons of 8.86 kev or greater excite the K radiation. The above factor indicates that deuterons of 8.2 Mev should behave similarly. Actually, deuterons with much less energy, even down to 4.5 Mev, are able to produce this effect. From the above relationship the incident energy of 10 Mev should be scarcely sufficient to excite the K radiation of gallium ($Z=31$), whereas in fact such deuterons will excite atoms as heavy as $Z=38$. This ability of the heavy particle to communicate more energy to the electron indicates the inadequacy of the simple treatment.

A more realistic treatment of the emission process based upon the Born approximation principle, as carried out by Henneberg, yields results that are not greatly in disagreement with those observed in this investigation. The theoretical expression shows the number of K electrons ejected by a constant excitation to increase progressively as the atomic number of the target decreases. Thus if in Fig. 2 the theoretical expression is adjusted at atomic number 34 to agree with the experimental after allowance for absorption is made, then its course is indicated by the dotted curve. To obtain the expected experimental curve the derived values must be multiplied by a reduction factor due to the absorption of the x-rays in an air path of 6 cm, an aluminum foil 0.0025 cm and a small effective absorption in the target. These total factors are of the order 0.6, 0.1 and 10^{-6} for atomic numbers 30, 24 and 16, respectively, thus yielding a maximum as observed. The principal disagreement is that the theory would predict a considerable yield of K x-rays for elements of atomic number greater than 38, which are not observed.

An approximate value can be ascribed to the cross section for the process of x-ray emission by the heavy particle. For the iron target under the conditions of the experiment, the theory of Henneberg would predict a cross section of about 3×10^{-21} cm^2. Experimentally 10^{14} incident particles passing through a small volume of iron containing 10^{18} particles was sufficient to blacken the photographic plate at a distance of 6 cm. By estimating the number of photons required to blacken unit area of the plate, a guess could be made of the total number of photons emitted, and hence the cross section. Such considerations lead to a value 10 to 100 times greater than the theoretical, but the difference cannot be regarded as outside the limit of error in the calculation.

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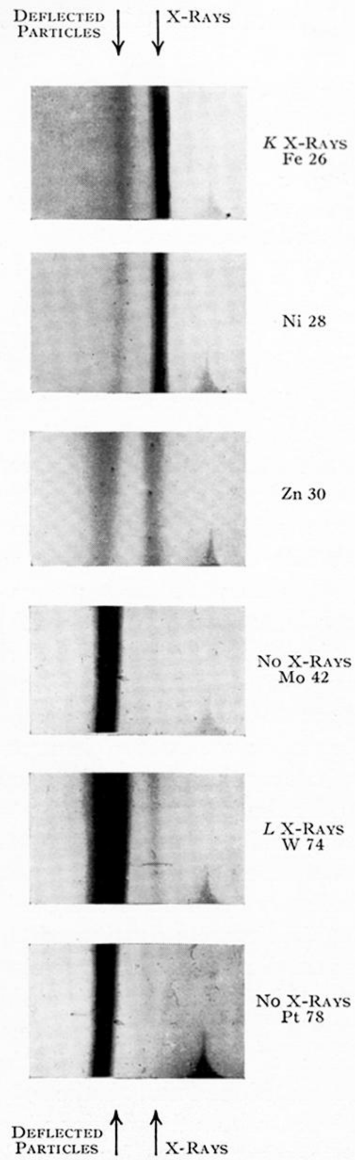

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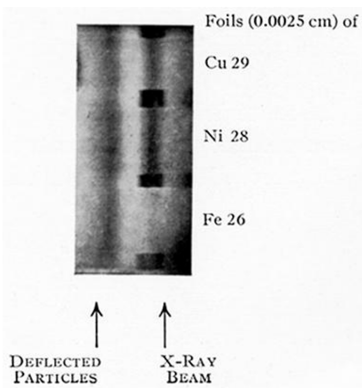

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