The Excitation of Characteristic X-Rays by Protons

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A qualitative study of the x-rays produced by protons of 1.76 Mev energy shows that these rays are the characteristic K and L radiations from the targets used. The variation of intensity with proton energy and with atomic number is found to be in agreement with that expected theoretically.

INTRODUCTION

IN the process of calibration of instruments intended for studies of nuclear disintegrations produced by protons of 2 million electron volts energy, x-radiation was observed to come from several targets in considerable intensity, while other targets showed a much lower intensity. It seemed advisable to make a qualitative study of the properties of this radiation, if only to safeguard interpretations of specifically nuclear phenomena.

Bothe and Franz[1] have shown that under alpha-particle bombardment x-rays characteristic of the target material were produced without the usual continuous background, and that the intensity of the radiation rose rapidly with increasing energy of the alpha-particles. Gerthsen and Reusse,[2] using protons of 150 kilovolts energy and sensitive Geiger counters to detect the radiation, found evidence for the excitation of Al_K, Mg_K and Se_L radiation, but observed no radiation from a target of intermediate atomic weight, Mn. These workers suggested the interpretation which is amplified in the discussion to follow. Henneberg[3] has calculated the probability of excitation of the K radiation from Al as a function of proton energy and his results were found to be in agreement with the observations of Gerthsen and Reusse. Several other observers,[4] using low energy protons, have studied the x-radiation from protons with sensitive detecting instruments and have also concluded that they are characteristic of the target.

The present observations extend the range of proton energies to much higher values and include a wide variety of targets. When the absorption of the x-rays by the air, the target, and other absorbing materials in their path is taken into account the results are found to agree with those predicted from an extension of Henneberg's calculations.

EXPERIMENTAL

The protons were accelerated to high speeds in a small "cyclotron"[5] and directed against targets mounted in the vacuum chamber. For the study of the x-ray intensity as a function of proton energy, aluminum absorbing foils of graded thickness were inserted in the path of the proton beam. Preliminary calibrations of the stopping powers of the foils with alpha-particles insured an accurate knowledge of the reduced energies of the proton beam. The initial energy of the protons was calculated from the resonance conditions and geometry of the cyclotron. The current of protons striking the target (mounted in a shallow Faraday cage) was 5.0 microamperes. For the purpose of measuring relative x-ray intensities an electrometer was used to measure the charge collected in a given time interval on an 8 microfarad condenser connected to the target; various x-ray intensity measurements could then be compared for equal numbers of incident protons.

The target was mounted at an angle of 45° to the direction of the proton beam and to the direction of observation. See Fig. 1. The radiations emerged from the target through a vacuum-tight mica foil, and after passing through lead collimating apertures, entered the ionization

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[1] Bothe and Franz, Zeits. f. Physik **52**, 466 (1928).
[2] Gerthsen and Reusse, Physik. Zeits. **34**, 478 (1933).
[3] Henneberg, Zeits. f. Physik **86**, 592 (1933).
[4] Peter, Ann. d. Physik **27**, 299 (1936); Hoffmann, Physik. Zeits. **37**, 694 (1936).
[5] Livingston, Rev. Sci. Inst. **7**, 55 (1936).

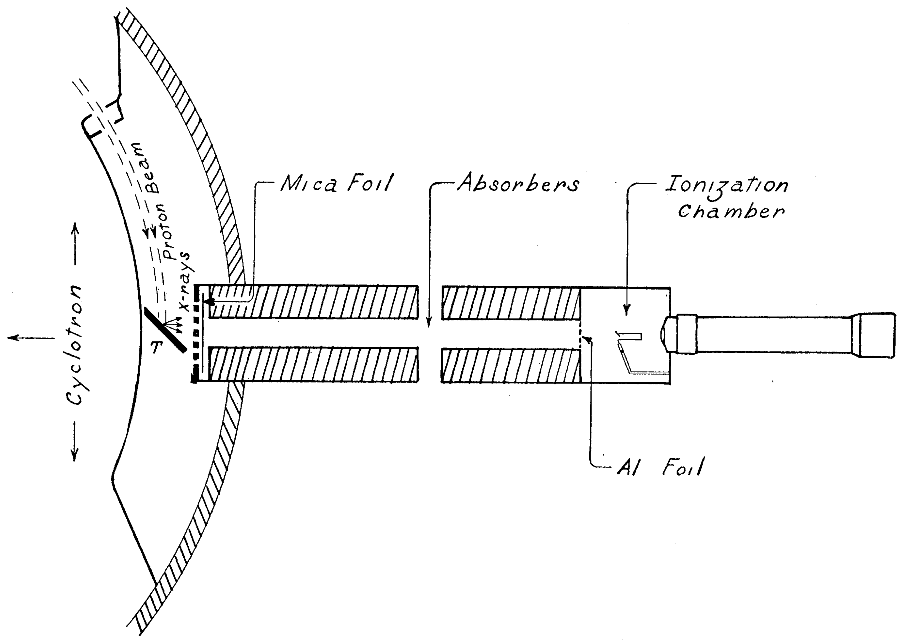

FIG. 1. Schematic diagram of the experimental arrangement for observing x-rays from proton bombardment.

chamber. This was a quartz fiber electroscope, patterned after those developed by Lauritsen,[6] in the form of a thin-walled brass cylinder of 2.5 cm radius and 5 cm length containing air at atmospheric pressure, with a thin Al window 2 cm in diameter over the end. Measurements of the voltage sensitivity together with a roughly computed capacity made it possible to estimate the charge sensitivity and thus absolute intensities.

Before entering the ionization chamber the radiation had to traverse a certain thickness of the target, a mica window of 2×10^{-3} cm thickness (about 20 cm air equivalent absorption for x-rays of $10>\lambda>0.7$A), 18 cm of air path and a thin Al window of 2×10^{-4} cm thickness (about 2.5 cm air equivalent). This served to absorb largely those x-rays of wave-length greater than about 3A, and so led to low intensities for the radiation from light targets.[7] In the discussion to follow this plays an important role in the interpretation of the results.

The identification of the radiation as x-rays was accomplished by studying the absorption in thin aluminum foils placed in front of the electroscope, and by the observation that a crossed magnetic field sufficient to deflect electrons of 100 million volts energy had no effect on the intensities observed in the ionization chamber.

RESULTS

(a) Absorption measurements

A study of the absorption in aluminum foils of the radiation from a Zn target resulted in the data plotted logarithmically in Fig. 2. The absorption coefficient of 42.3 cm^2/g of Al deduced from the slope of the straight line indicates a wave-length of 1.47A, and is in good agreement with the mean value of the K lines of Zn, which is 1.43A. The experimental points fall on a well-defined straight line, indicating that the radiation is monochromatic to within 0.1A and that there is no appreciable intensity of continuous radiation, a fact which is expected from theoretical considerations.[8] The L radiation from Zn would

[6] Crane, Lauritsen and Soltan, Phys. Rev. **44**, 514 (1933).

[7] High intensities from a carbon target originally observed were found to be due to the brass target holder.

[8] The intensity of continuous radiation is known to be proportional to $(e^2/Mc^2)^2$, where M is the mass of the emitting particle. For this reason the continuous radiation

be of about 12A, and so would be completely absorbed in the air path. This evidence, combined with the relative intensity measurements to be discussed, makes it seem probable that the radiation in each case is characteristic of the target.

(b) Voltage excitation measurements

The relative intensity of the radiation from Zn as a function of the proton energy is given in Fig. 3. This shows the intensity dropping below the observational limit of this experiment at about 600 kilovolts. The curve was calculated theoretically (cf. "Discussions and Calculations") and fitted to the data at the 1.37 Mev point; the experimental points are found to agree within the limits of error. Similar data taken for other targets (Mg and Mo) show the same features, but with different "slopes" in accordance with the predictions of the theory for the different K wave-lengths.

(c) Variation with atomic number of the target

The relative intensities from the various targets used, for equal currents of 1.76 Mev protons, are plotted in Fig. 4. These data indicate the existence of two peaks, one near atomic number 26 and another in the rare earths group. These peaks are presumably caused by the K and the L radiations from the respective targets. The steep descent from each peak on the side of the higher atomic numbers is ascribed by the theory to the decreasing probability of excitation of the higher energy K and L radiations from these targets by protons of a given energy. The low intensities on the low atomic number sides of the peaks are due to the exceedingly strong absorption of the air and other absorbing materials for the low energy radiations from these targets. A corrected theoretical curve (cf. "Discussions and Calculations") for the K radiation is fitted to the observed data at Fe, and seems to represent the data adequately. The curve for the L radiation (second peak) was drawn by analogy.

(d) Absolute intensity estimates

In Figs. 3 and 4 the intensities are given in arbitrary units representing the number of scale divisions traversed in a 6 sec. interval by the electroscope fiber—per 1.0 microampere of proton current—incident on the target. From the measured voltage sensitivity and the com-

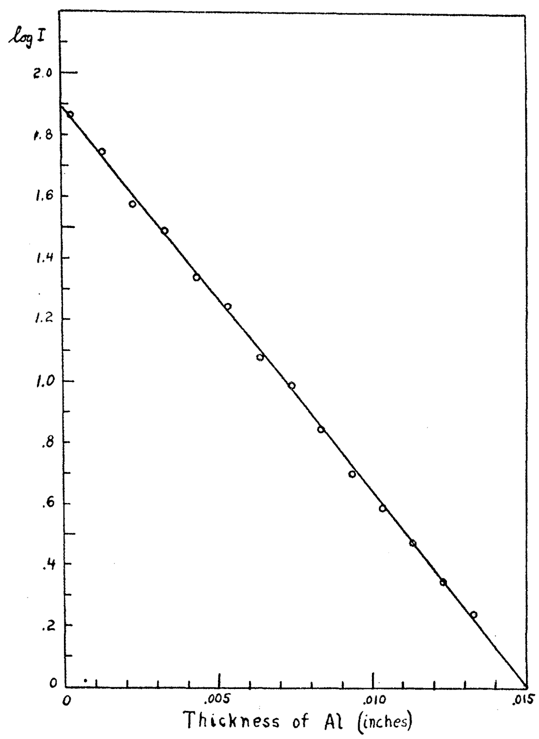

FIG. 2. Absorption in aluminum of the radiation from a zinc target bombarded by 1.76 Mev protons.

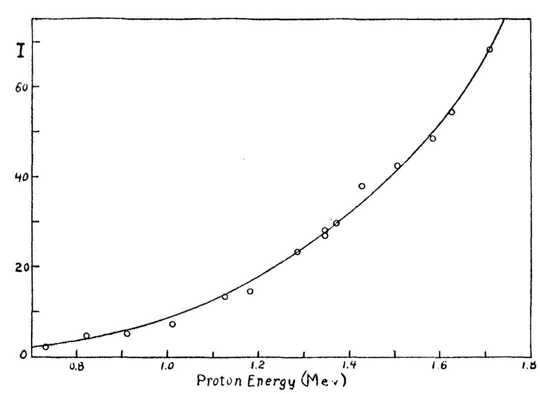

FIG. 3. Variation of x-ray intensity from a zinc target with proton energy. The curve is calculated theoretically and matched to the data at one point.

from protons will be very weak compared to the continuous radiation observed in excitations by electrons. Radiation from the free electrons accelerated by proton impact will have a minimum wave-length of 32A due to conservation laws and so would be unobservable in these experiments.

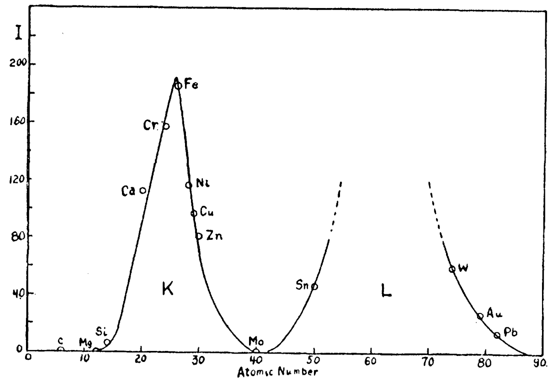

FIG. 4. Variation of x-ray intensity with atomic number of the target. The curve representing the K peak was calculated theoretically and matched to the experimental data at the point for Fe. The L curve is drawn by analogy.

puted capacity of the electroscope a charge sensitivity of about 2×10^{-5} e.s.u./div. was obtained. For the peak intensity on Fig. 4 (Fe) this leads to the value of 5×10^{-4} e.s.u./sec. for each cubic centimeter of the ionization chamber (at a distance of 20 cm from the target) with a proton current of 1.0 microampere. A theoretical estimate of the intensity to be expected, corrected for the special conditions of this experiment, gave roughly 5×10^{-3} e.s.u./cm^3 sec. This discrepancy is not entirely surprising in view of the uncertainties in the corrections.

DISCUSSION AND CALCULATIONS

Henneberg[3] gives a graphical representation of the calculated cross section for the excitation of K radiation as a function of proton energy and atomic number, $\varphi(E, Z)$. For small E the dependence is approximately: $\varphi\sim E^4/Z^{12}$. The high absorption of the target for its own K radiation necessitates the superposition of a correction for it upon the thick target correction due to the penetration of the protons. Because of the 45° incidence of the proton beam the x-rays come through a thickness of target equal to the proton penetration, and the intensity of the emergent x-rays is proportional to:

$$\Phi(E_0, Z)=\int_0^{x_0}\varphi(f(x), Z)e^{-\kappa(Z)(x_0-x)}dx, \quad (1)$$

where $E=f(x)$ is the energy range relation for protons[9] in the target $(f(x)\sim x^{2/3})$; x_0 is the maximum penetration of the protons $(E_0=f(x_0))$; $\kappa(Z)$ is the x-ray absorption coefficient of the target material just above the K absorption limit in the wave-length scale. The numerical evaluation of (1) as a function of E_0 with $Z=30$ gave the curve shown in Fig. 3, after a matching with the experimental data at one point. The variation of E_0 from 1.76 Mev to 0.73 Mev is equivalent to a variation of x_0 from 0.0018 cm to 0.0005 cm in Zn.

In order to account for the observed variation of the x-ray intensity with atomic number (Fig. 4) it is necessary to consider the absorption of the various x-ray frequencies by the air, the mica and the Al foils. It is also necessary to correct for the relative sensitivity of the ionization chamber for radiations of various wave-lengths. Consequently, the peaks arise from the following type of function (giving the number of ions collected per second by the electroscope):

$$I=NN_P\Phi(E_0, Z)\cdot(\omega/2)e^{-\tau(\lambda)d}\cdot S. \quad (2)$$

N is the number of atoms per cubic centimeter of the target; N_P is the number of protons incident per second. ω is the fraction of a sphere, centered at the target, subtended by the window of the ionization chamber; it is divided by 2 in order to allow for the fact that the grid at the mica window intercepts half the x-ray beam. $\tau(\lambda)$ is the air absorption coefficient which varies with the wave-length of the radiation, λ. The absorption path for the x-rays in air equivalent cm is given by d. Finally, S is a sensitivity factor for the ionization chamber. If we take into account only the ions created by the photoelectrons (which lose 32.5 volts per ion pair formed[10]), the number of ions collected by the electroscope fiber when n quanta of energy $h\nu$ (in volts) pass through a chamber of length l is:

$$I=nS=n\frac{h\nu-W}{32.5}(1-e^{-\tau(\lambda)l})U. \quad (3)$$

W is the average ionization potential of nitrogen and U is the fraction of the ions recorded.

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[9] Mano, Ann. de physique **1**, 407 (1934); Rosenblum, ibid. **9**, 408 (1928).

[10] Gray, Proc. Roy. Soc. **156**, 578 (1936).

The magnitude of U is determined by the amount of recombination which takes place. This was estimated by dividing the electroscope into sections of spherical condensers in each of which there is a uniform distribution of sources of ions and a distribution of sinks proportional to $\alpha n_1 n_2$, where α is the recombination coefficient (1.6×10^{-6} cm^3/sec. for air at N. T. P.) and n_1, n_2 the density of positive and negative ions. In this way, S was found to vary by a factor 5 from Ca to Br. It is 0.41 for the peak intensity (Fe).

The function (2) is quite sensitive to S and to the equivalent absorption thickness d; the agreement between theory and experiment as shown by Fig. 4 is as good as could be expected.

I as given by (2), multiplied by the charge on an ion, represents the charge collected by the electroscope per second. The factors $\frac{1}{2}N_P N\Phi$ give the number of quanta emerging from the target per second ("$\frac{1}{2}$" because they may only emerge from one side of the thick target). For Fe this was calculated to be 2×10^{12} quanta per second. Multiplication by $\omega e^{-\tau d}$ gives n, the number of quanta which enter the ionization chamber per second. Then, using (3), we obtain $enS/v = 5\times10^{-3}$ e.s.u./cm^3 sec. as the charge collected per sec. per cm^3 of ionization chamber (volume v), for the Fe radiation.

The evidence for the identification of the first peak of Fig. 4 with the characteristic K radiations is very strong. It seems reasonable that the second peak should be due to L radiation, although no calculations have been attempted and the data are scanty. The curve obtained theoretically for the K radiation is sensitive to the many corrections. Accordingly no strictly quantitative check with the theory can be claimed in this respect. However, qualitatively at least, the agreement is sufficiently satisfactory to justify the interpretation given.

It may be of some significance to x-ray workers that this offers a method for the production of K radiation from light elements without the usual continuous background. The results gain interest also from the fact that the excitation of K radiation by protons plays a part in the determination of the rate at which protons lose energy in passing through matter. The experimental confirmation of the theoretical predictions thus lends support to the use of the theory in determining range-energy relationships.

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