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The Primary Ionization of High Energy Electrons in Nitrogen and Neon

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A large expansion chamber in a magnetic field of about 400 gauss is used to study the tracks of high energy beta-rays produced by bombarding a lead screen inside the chamber by gamma-radiation from radon. Two photographs at right angles are taken, and the tracks examined by projection on to a screen in their original configuration. Measurements are made of the number of primary ions per cm of path produced in nitrogen and neon. The results in nitrogen can be expressed approximately by the relation:

$$I = 19\beta^{-1.15\pm 0.15},$$

and in neon by the relation:

$$I = 12.6\beta^{-1.35\pm 0.15},$$

where I is the primary ionization in ions per cm at normal temperature and pressure, and β is the velocity of the beta-ray in units of the velocity of light. Measurements on a few tracks in oxygen agree within experimental error with the results of Williams and Terroux. The primary ionization of the positive electrons observed is indistinguishable from the negative electrons. Comparisons are made with the theoretical calculations of Bethe, Moller, and Williams, and the agreement is satisfactory over the range of velocities used. The magnitude obtained for the primary ionization in nitrogen corresponds, on the basis of the formula obtained by hydrogen like wave functions, to an average ionization potential of 16.6 volts for the five outer electrons in the nitrogen atom, which is very near its minimum ionization potential. Theoretical calculations are made for neon, using ionization potentials for each electron calculated from critical absorption wave-lengths. The experimental results are somewhat greater than those calculated from the theory, but are as close as the somewhat arbitrary assumptions involved would allow one to expect. The variation of primary ionization with velocity checks well for values of less than 0.97, but the predicted increase for very high energies is not observed.

INTRODUCTION

VERY little experimental work has been done on measuring the primary ionization produced by high energy electrons. C. T. R. Wilson[1] in 1923, counted the number of primary ions in portions of nine different tracks, and found for fast beta-particles that the primary ionization varied from 18 to 22 ions per cm, with an average of about 20. No measurements were made on the velocities of the electrons, but they were estimated to be greater than 2×10^{10} cm per sec.

Williams and Terroux[2] in 1930, using an expansion chamber placed in a magnetic field of about 400 gauss, measured the primary ionization produced by the beta-rays from an old radium emanation tube in oxygen and hydrogen. The results of measurements of the primary ions on 108 tracks in hydrogen were shown to be expressible by the equation:

$$I = 5.2\beta^{-1.5\pm 0.2},$$

and the results on 72 tracks in oxygen by the equation:

$$I = 22\beta^{-1.1\pm 0.2},$$

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[1] C. T. R. Wilson, Proc. Roy. Soc. **A104**, 1, 192 (1923).

[2] E. J. Williams and F. R. Terroux, Proc. Roy. Soc. **A126**, 289 (1930).

where I is the number of primary ions per centimeter of path at normal temperature and pressure, and β is the velocity of the electron in units of the velocity of light.

From the standpoint of classical mechanics, the ionization of a molecule by an electron is regarded as a collision between two particles, the moving electron and one of those in the molecule, in which sufficient energy is given the latter to remove it entirely from the molecule. The classical theory was worked out by J. J. Thomson,[3] who obtained the following expression for the primary ionization:

$$I=2\pi ne^4/mv^2J$$

where n is the number of electrons per unit volume, e and m the charge and mass of the electron, respectively, v the velocity of the incident electron, and J the ionization energy, or energy required to remove an electron from its atom. Williams and Terroux found that the observed primary ionization was five to six times as great as predicted by the theory, as well as showing a much smaller variation with velocity than the inverse square law.

The quantum theory has been applied to the problem by several authors. Gaunt[4] in 1927, applied the theory to distant collisions, in which case the incident particle moves essentially in a straight line. Its passage gives rise to a perturbing potential that varies in known manner with the time. His results are obtained by solving the Schrödinger equation for the atomic electron alone. The application of Gaunt's theory to primary ionization is discussed by Williams,[5] who shows that the theory gives results which are closer to the experimental facts than the classical theory, but still in considerable disagreement.

A more rigorous treatment of the problem has been made by Bethe[6] on the basis of Born's theory of collisions. As distinguished from Gaunt's theory, Bethe's treatment is statistical, not dealing with the individual electrons. He represents the atomic electrons by hydrogen-like wave functions, and assuming that the velocity of the moving electron is large compared with the Bohr orbit velocity of the atomic electrons, and is small compared with the velocity of light, finds a solution of Schrödinger's wave equation for particles in each other's field and the field of the nucleus. Bethe calculates the perturbation only as far as the first approximation, and obtains the following expression for the primary ionization of a hydrogen-like atom:

$$I=(0.285)(2ne^4/mv^2J)\log(42mv^2/J). \quad (1)$$

For the case of relativistic velocities of the moving electron, Moller[7] and Williams[8] obtain an expression which should hold for high energy electrons. The primary ionization is found to be given by:

$$I=(0.285)\frac{2\pi ne^4}{mv^2J}\left[\log\frac{42mv^2}{J}-\log\frac{1}{1-\beta^2}-\beta^2\right]^9. \quad (2)$$

The present work was undertaken to obtain more experimental data on the primary ionization of fast beta-particles so that comparisons could be made with the above theoretical equations.

Apparatus and Procedure

The experimental method used in the present work is briefly as follows: A large expansion chamber is placed in a magnetic field produced by two Helmholtz coils. High speed electrons produced by bombardment of a lead strip inside the chamber by gamma-radiation from radon, produce tracks which are bent into arcs of circles, and from measurements made on their radii of curvature, the energies of the electrons are computed. Two photographs are taken at right angles, and the tracks obtained are studied by replacing the film in projectors arranged so that the tracks are projected on a screen in their original size and configuration. Measurements of the primary ionization are made by counting the

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[3] J. J. Thomson, Phil. Mag. **23**, 449 (1912).

[4] J. A. Gaunt, Proc. Camb. Phil. Soc. **23**, 732 (1927).

[5] E. J. Williams, Proc. Roy. Soc. **A130**, 328 (1931).

[6] H. Bethe, Ann. d. Physik **5**, 325 (1930); Zeits. f. Physik **76**, 293 (1932).

[7] C. Moller, Ann. d. Physik **14**, 531 (1932).

[8] E. J. Williams, Proc. Roy. Soc. **A135**, 108 (1932); **A139**, 163 (1933).

[9] Dr. Bethe has pointed out in conversation with one of the authors that this formula cannot be satisfactorily applied to atoms other than hydrogen, due partly to the way in which energy transferred from incident electron is divided between excitation and ionization, which varies for different atomic types. A new formula fitting each particular atom must be developed in order to experimentally check the theory.

number of ion groups per centimeter length of the images of the tracks on the screen.

The expansion chamber is ten inches in diameter, and of the diaphragm type, similar in many respects to that described by Locher.[10] The magnetic field is obtained by a pair of Helmholtz coils which surround the chamber, and produce a field of about 400 gauss, uniform to within 1.5 percent over the chamber. Arc lamps are used as a source of illumination, and the arc resistances are short-circuited at the time of expansion in order to provide sufficient illumination for photographing the very thin tracks produced by high energy electrons.

Two matched Leica cameras with $f:3.5$ lenses are used to obtain two photographs at right angles. In order to bring the entire chamber into focus, it was necessary to rebuild the cameras so as to tilt the lenses about 7° to the normal to the film, as described by Blackett.[11] Reconstruction of the tracks is accomplished by inserting the negative film in projectors arranged so that the optical system is an exact replica of that used in photographing the tracks. The general method is similar to that described by Blackett[11, 12] and others.[13, 14]

The gamma-radiation from radon tubes is used to produce the high energy electrons used in this work. A large trapezoidal-shaped block of lead 12 inches long, containing a $\frac{1}{4}$ inch hole through its center, is used to collimate the beam, and shields all parts of the chamber from the gamma-radiation by at least 10 inches of lead. The narrow beam of gamma-rays entering the chamber is filtered through about $1\frac{1}{4}$ inches of lead as well as the $\frac{3}{16}$ inch glass wall of the chamber, and strikes a lead strip placed inside the chamber, from which high energy electrons are emitted. The average energy of the tracks measured is about one million electron volts.

The direct counts of primary ions were reduced to normal temperature and pressure, and small corrections were applied to correct for the presence of water vapor in the chamber, and for the possibility of two primary ions being produced so close together as to be unresolvable.

This latter correction depends upon the size of the drops and their average distance apart, and involves more uncertainty than the other corrections applied. The average diameter of the drops determined by measurements on the film with comparator was found to be 0.4 mm. However, droplets may be resolved even when they overlap considerably, and it is assumed that the resolution of the droplets is actually limited by the resolving power of the eye, which is 0.1 mm. The correction was calculated on a pure probability basis. The probability that an electron will go at least a distance l before colliding with a molecule, denoted by $f(l)$, is given by[15]

$$f(l)=e^{-l/\lambda}$$

where λ is the "mean free path" of the electron. Letting I be the true number of ions per cm, and I_0 the observed member, we have

$$I_0=Ie^{-lI}$$

where λ has been put equal to $1/I$. The equation may be solved graphically for I as a function of I_0, using $l=0.1$ mm. The corrections are of the order of 10 percent to 15 percent in nitrogen and 7 percent to 10 percent in neon, depending on the energy of the incident electron.

The effect of the presence of water vapor in the chamber on the number of ions per cm measured was estimated from the known stopping power of water vapor and found to make an error of the order of 0.3 percent, which was neglected.[16]

EXPERIMENTAL RESULTS

The results on the measurements of 100 tracks in nitrogen is shown in Fig. 1. The six points on the curve are obtained by dividing the tracks measured into six energy groups and plotting the "center of gravity" of each group. It is seen that the primary ionization decreases with increasing energy of the incident electron, apparently approaching asymptotically a constant value. In Fig. 2 are shown the same data plotted on a logarithmic scale, in order to show the variation

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[10] G. L. Locher, J. O. S. A. and R. S. I. **19**, 58 (1929).

[11] P. M. S. Blackett, Proc. Roy. Soc. **A123**, 613 (1929).

[12] P. M. S. Blackett, Proc. Roy. Soc. **A102**, 294 (1922); **A103**, 62 (1923); J. Sci. Inst. **4**, 433 (1927); **6**, 184 (1929).

[13] L. F. Curtiss, Nature **123**, 529 (1929); Bur. Standards J. Research **4**, 663 (1930); **8**, 579 (1932).

[14] P. Auger, Thesis, University of Paris (1926).

[15] Jeans, *Dynamical Theory of Gases*, 3rd ed., pp. 257.

[16] F. N. D. Kurie, Rev. Sci. Inst. **3**, 655 (1932).

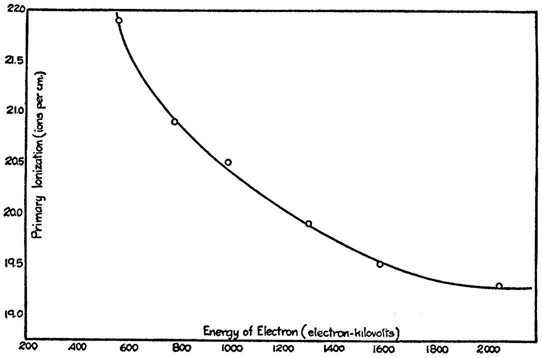

FIG. 1. Primary ionization in nitrogen.

with velocity. If a straight line is drawn as near as possible through the experimental points, its slope shows that the primary ionization varies as the -1.15 power of the velocity, and the experimental results for nitrogen may be represented by the equation:

$$I = 19\beta^{-1.15\pm 0.15}.$$

On the same figure is plotted a theoretical curve calculated from the wave mechanical expression for primary ionization given by Eq. (2). Since the ionization potentials of the two K electrons in nitrogen is very large compared to that of the L electrons, we may assume that only the five outer electrons in the nitrogen atom are available for ionization. If the average ionization potential of these outer electrons is taken as 16.6 volts, which is very near the minimum ionization potential for the nitrogen molecule, the theoretical curve may be made to fit the observed data. The dotted curve of Fig. 2 is plotted on this basis. The ionization potentials for each electron in the nitrogen atom is not known. In general,

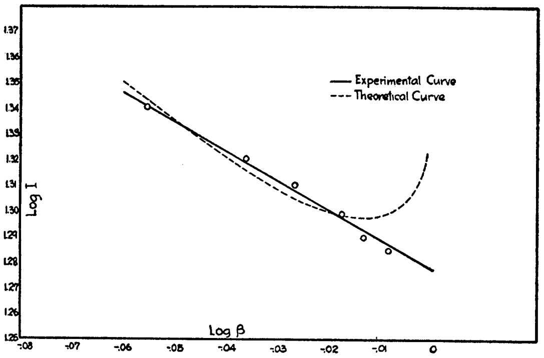

FIG. 2. Logarithmic curve for nitrogen.

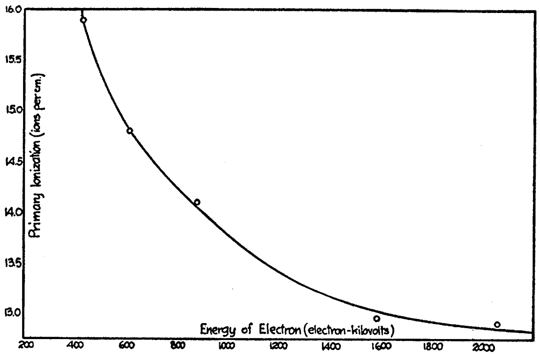

FIG. 3. Primary ionization in neon.

however, the minimum ionization potentials observed correspond to that for the $2p$ electrons, and that for the $2s$ electrons is somewhat higher, which tends to make the experimental results somewhat higher than that predicted by the theory. The magnitude calculated on the classical theory is only about one-fourth that observed.

The experimental and theoretical curves have approximately the same slope over the range of velocities investigated, and agreement with variation with velocity is satisfactory. However, for values of the velocity greater than 0.97 the velocity of light, the theoretical curve shows an increase with velocity, increasing indefinitely as the velocity of the electron approaches that of light. Although the data obtained do not extend very far above this predicted minimum point, there is no indication of this increase, and observations on two or three tracks of very high energy undeflected in the magnetic field show a primary ionization approximately the same as those of the highest energy on the previous graph. The rise in the theoretical curve, however,

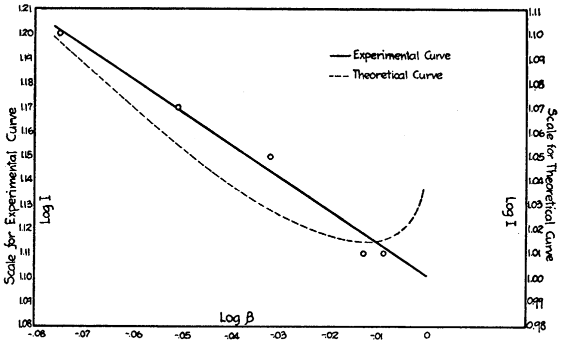

FIG. 4. Logarithmic curve for neon.

does not occur until very high energies are reached, and no conclusions can be drawn as to the existence of this increase at high energies.

The results on neon are shown in Figs. 3 and 4. The data are compiled and plotted by the same method as used for nitrogen, except that the theoretical curve is moved up vertically so that it can be plotted on the same scale as the experimental curve. The experimental results in neon may be represented by the equation:

$$I = 12.6\beta^{-1.35\pm 0.15}.$$

The ionization potentials for each of the neon electrons is known from measurements on critical absorption wave-lengths, and these correspond to the molecule since neon is monatomic; and thus more accurate comparisons with theory may be made. The experimental results show that the primary ionization varies as the -1.35 power of the velocity, and is within experimental error in agreement with the theoretical predictions. As in the case of nitrogen, however, the increase at high velocities is not observed. The magnitude observed is about 12 percent higher than the calculated on the basis of the formula obtained by hydrogen-like wave functions but are as close as the somewhat arbitrary assumptions involved would allow one to expect. The observed magnitude is six times the classical value.

A few tracks in oxygen have been measured to compare the results with those of Williams and Terroux, and the values obtained check their results closely. Two or three tracks, definitely due to positive electrons, show no distinguishable difference in primary ionization from the negative electrons of similar energy on which ion counts were made. Work is now being done on measurement of the primary ionization in argon and preliminary results obtained indicate a lower value than would be expected by Bethe's formula (2). A complete account of this work will, however, be published soon.

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OCTOBER 15, 1936 PHYSICAL REVIEW VOLUME 50

Disintegration Experiments on the Separated Isotopes of Lithium

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Observations made with targets of 18 micrograms of Li^6 and 200 micrograms of Li^7 under proton and deuteron bombardment have given the following results. (1) Two groups of protons with mean ranges of 25.4 cm and 29.6 cm air-equivalent are emitted by Li^6 under deuteron bombardment at 540 kv. No group of such range was found for Li^7 under similar conditions. (2) Neutrons are emitted by Li^6 under deuteron bombardment at 300 kv and above. (3) Short period beta-ray activity was observed from Li^7 under deuteron bombardment at 500 kv and above with no observable activity from Li^6 under similar conditions. (4) Gamma-rays are emitted by Li^7 under proton bombardment in the neighborhood of 450 kv and of 1000 kv, with no observable gamma-rays or neutrons emitted from Li^6 with protons of these energies.

I. Introduction

While it is to be expected that the proper parent of most transmutation products may be assigned from energy considerations and mass spectrograph data, the origin of other products may be ambiguous, particularly in case a previously unknown nucleus is formed or the available energy is utilized only partially in a single process. Furthermore, certain nuclear processes in one isotope may be obscured by the products of another isotope. In these instances, the use of targets of single isotopes assumes special significance. An example of such work is that of Oliphant, Shire, and Crowther,[1] using

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[1] M. L. Oliphant, E. S. Shire and B. M. Crowther, Proc. Roy. Soc. **A146**, 922 (1934).