frequencies of oscillation would be possible. The accelerators, being longer, could have greater spacing and thus higher voltages could be applied. Hence it is feasible to produce nitrogen molecule ions with nearly two million electron volts energy by this method.

It is even possible to give considerable energy to very light ions by this method. Lithium ions could be accelerated to energies of at least one and a quarter million electron volts. Hydrogen or helium ions could be given about one million electron volts. Since this method requires no elaborate equipment it is a practical method even for such very light ions.

The comparative simplicity of this method should be emphasized. The principal requirements are the oscillator tube and the plate voltage transformer. If these two have a power rating of 5 kw, it is possible to produce mercury ions with nearly two million electron volts energy. To produce ions with energies of 2.85 million electron volts, the power rating must be 10 kw. The construction of the tube itself presents no difficulties, especially if one uses the type of construction where the accelerators are individually supported. With such modest equipment as this, it is possible to study the little known properties of very fast positive ions.

The authors take pleasure in expressing their gratitude to Professor Ernest O. Lawrence for his constant interest in this work and for his many valuable suggestions.

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The Production of X-Rays by Swiftly Moving Mercury Ions

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A study has been made of the production of soft x-rays (4 to 9A) by mercury ions having energies up to 2.38 million electron volts. The ions were accelerated by the method of Sloan and Lawrence. It has been shown conclusively that the x-rays are actually produced by the ions and not by electrons. Through absorption measurements in aluminum and in air the wave-length of the radiation has been determined for the following targets: aluminum, sulfur, bromine, molybdenum, silver, tin and lead. No radiation could be detected from lithium, boron, carbon, oxygen, sodium, nickel or copper. The wave-lengths were characteristic of the target in the case of aluminum, sulfur, bromine, lead and probably molybdenum. The radiations from tin and silver were not characteristic either of the target or of mercury. The variation in x-ray intensity as a function of the energy of the ions has been studied for targets of lead, bromine, molybdenum, silver and aluminum. The x-ray intensity is found to increase very rapidly with the energy of the ions. No radiation could be detected from bromine, molybdenum, or aluminum when the ions had energies less than 700 kv, nor from lead or silver when the ions had energies less than 400 kv. It is found that at least one in every 2000 mercury ions produces an x-ray quantum when silver is bombarded. The ions in this case had 2.38 million electron volts and produced 2600 volt quanta. A theory is proposed to explain the excitation of x-rays by positive ions, wherein it is assumed that the ion and the target atom temporarily form a quasi-molecule. Loss of some of the inner electrons by one of the atoms as the molecule breaks up necessitates refilling of the empty levels and consequent radiation. Support for this theory is afforded by the agreement between the calculated and the experimental values for the minimum energy necessary for excitation.

INTRODUCTION

IT has been known for some time that x-rays can be produced by positively charged particles such as the alpha-particle[1] and the proton.[2] There has been, however, no observation of x-radiation produced by heavier particles. On the other hand, until recently there has not been available a method of giving large energies to heavy ions. Such a method has been developed by Sloan and Lawrence[3] and extended by Sloan and the author.[4] This method has made it possible to work with mercury ions having energies up to

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[1] Chadwick, Phil. Mag. **24**, 594 (1912); Bothe and Fränz, Zeits. f. Physik **49**, 1 (1928); **52**, 466 (1928).

[2] Thomson, Phil. Mag. **28**, 620 (1914); Gerthsen, Ann. d. Physik **85**, 881 (1928); Barton, J. Frank. Inst. **209**, 1 (1930); Lawrence and Livingston, unpublished work.

[3] Sloan and Lawrence, Phys. Rev. **38**, 2021 (1931).

[4] Sloan and Coates, Phys. Rev., preceding article.

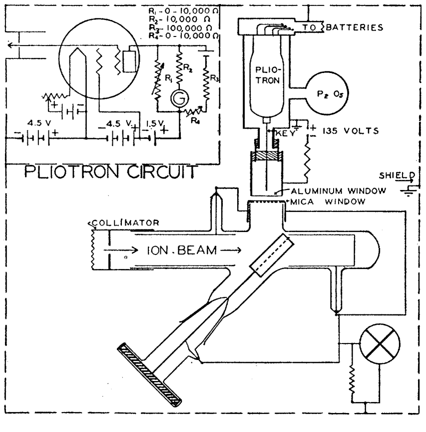

FIG. 1. Collector and ionization chamber with electrical circuit.

2.38 million electron volts. It has been shown in this work that these ions are able to produce an appreciable amount of x-radiation.

APPARATUS

For production of the ions

The method of producing the high speed ions has been described in previous papers.[3, 4] Fig. 1 of the preceding paper shows schematically the tube used. It will be desirable to refer to this figure, and point out the features which were designed to prevent spurious results.

The end of the accelerating system is a tube *D*, which is provided with two lead rings. These rings prevent x-rays or electrons from reaching the ion collector by travelling between the accelerator tubes and the glass walls. X-rays or electrons, which travel through the tube *D*, are stopped by the lead diaphragms in the collimator *F*. Electrons reaching the point *E* are deflected downward by the electrostatic field and also horizontally by the magnetic field. The horizontal deflection eliminates electrons reflected from the bottom deflecting plate. That these precautions were adequate to prevent spurious results was shown by experiments described below.

For detection and measurement of the x-rays

The apparatus used for the study of the x-rays is shown in Fig. 1 of the present paper. The collector for the ion beam which was made of Pyrex glass was waxed in to the brass collimator tube. The glass walls were shielded by metal so as to prevent charges from building up on them. The metal parts were all electrically connected so as to form a Faraday cage. The latter was connected to an electrometer which measured the intensity of the ion beam.

The targets were mounted on a rectangular metal box, which could be rotated by means of a ground joint. Thus it was possible to compare four different targets under identical conditions. One of the targets was always molybdenum which served as a standard. The position of the ion beam could be determined by observation of the fluorescence produced when the ions struck a zinc sulfide target. Thus the solid angle subtended by the ionization chamber could be readily calculated. In some of the earlier measurements this interchangeable target was not used. However it was found that targets could be changed by opening up the tube without appreciably altering conditions, since results could be repeated after changing from one target to another of the same material. Opposite the target a brass cap was waxed on to the glass. This cap was perforated by 59 holes each 2.5 mm in diameter. A sheet of thin mica (1.3 mg/cm^2) covered these holes so as to make the whole vacuum tight.

The radiation was first detected with a Geiger point counter, but the quantitative measurements were all made with an ionization chamber. The latter consisted of a copper cylinder surrounding and insulated from a No. 24 copper wire. The front was closed by thin aluminum (0.47 mg/cm^2). The chamber was filled with air at atmospheric pressure. The guard ring, as shown, was insulated by amber from the central electrode. The chamber was mounted on the brass shield enclosing the FP-54 pliotron by means of an ebonite sleeve. The whole formed a rigid unit which could be moved on a track so as to study the absorption in air. The whole apparatus was well shielded from other electrical circuits.

EXPERIMENTS SHOWING THE OBSERVED EFFECT TO BE GENUINE

Since x-radiation produced by mercury ions has not heretofore been observed it was necessary to show that the effect observed was really due to the ions and that it actually consisted of x-rays. First, it was shown that the observed results were not due to x-rays produced by electrons and scattered from the target. To prove this point, the beam of ions was prevented from striking the target by a foil known to be transparent to the x-rays. Under these conditions, no x-rays whatever could be detected. Next, it was shown that the effect was not due to cathode rays producing x-rays at the target. It was found that the x-rays were never affected by the application of magnetic fields and retarding potentials which were more than sufficient to eliminate cathode rays from the path leading to the target. Finally, extensive studies of the absorption of the radiation in different substances made it obvious that the radiation was electromagnetic in character. In particular, it was shown that the radiation could not consist appreciably of particles.

THE WAVE-LENGTH OF THE RADIATION

The wave-length of the radiation was determined in each case by measuring the absorption coefficients in aluminum and in air. In some cases the absorption in mica and in gold was also studied. The absorption curves (Fig. 2) show the logarithm of the ionization current as a function of the thickness of aluminum. In no case do the curves show any evidence for continuous radiation. Moreover, the fact that certain targets of medium atomic number gave no appreciable radiation, while targets of lower and higher atomic numbers did, is strong evidence that the radiation was characteristic rather than continuous. It is of interest to note that Bothe and Fränz[5] found only characteristic radiation excited by alpha-particles.

Aluminum

An effective wave-length for the *K* radiation of any element may be calculated by taking the weighted mean of the wave-lengths of the individual lines in the *K* spectrum. From this effective wave-length an effective absorption coefficient may be obtained from the tables of such coefficients.[6] In Fig. 2, the straight line corresponding to the absorption coefficient for the aluminum *K* radiation has been drawn, and it is seen that the experimental points fit the curve quite well. The data have been multiplied by a constant factor so as to make the point for zero absorber lie on the curve. These results seem to indicate that the radiation observed was the characteristic *K* radiation of aluminum (8.23A). A comparison with the other data in Fig. 2 (plotted on the same scale except in the case of bromine) brings out an interesting fact. The curves show that the aluminum foils were more transparent to the radiation from aluminum than to the shorter wave-length radiation from tin, silver, molybdenum, etc. These latter radiations had wave-lengths of from 4 to 5A. This result is of course necessary if the radiation from aluminum was really characteristic of aluminum. The absorption of this radiation in air was also measured. The measurement was rather inaccurate due to the necessity of using a very thin layer of air and of moving the ionization chamber. The result indicated a wave-length of 8.8A, which differs from 8.2A by less than the experimental error. Bothe and Fränz[5] observe that alpha-particles excite the aluminum *K* radiation with an intensity about 1000 times as great as that found in this work.

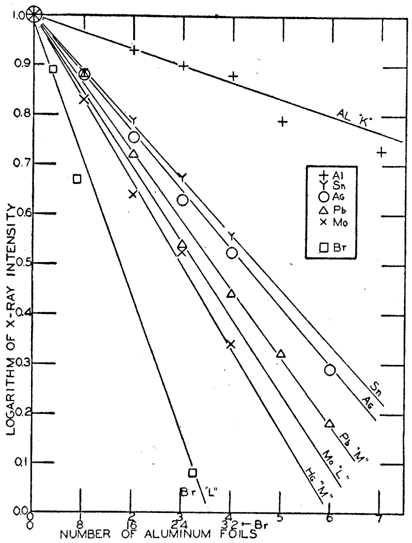

FIG. 2. Curves showing the absorption of the radiation in aluminum.

Sulfur

The sulfur *K* radiation involves more excitation energy than that of aluminum (2260 volts as compared to 1460 volts). Hence one might expect the probability of excitation and hence the intensity of the radiation to be less for sulfur than for aluminum under the same conditions. Such a result is found by Bothe and Fränz[5] in the case of

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[5] See reference 1.

[6] Siegbahn, *Die Spektroskopie der Röntgenstrahlen* (1932).

alpha-particle excitation. They find less and less intense K radiation from different targets as the atomic number increases until finally no K radiation can be detected. When a sulfur target was bombarded by the mercury ions a small amount of radiation was observed. The intensity was less than half that from aluminum. The absorption in aluminum could not be measured because of lack of intensity. However, measurements in air gave a mass absorption coefficient of 290. The value to be expected for the sulfur K radiation (5.3A) is 301. The agreement is well within the experimental error and it seems quite certain that what was observed was actually the sulfur K radiation.

Nickel and copper

The K radiations for nickel and copper require still more excitation energy (about 8000 volts). Hence the intensity here might be expected to be extremely small and probably unmeasurable. The L radiations are much too soft (about 15A) to reach the ionization chamber. When each of these elements was bombarded by the 2.38 million volt ions no radiation could be detected. It is therefore believed that the ions could not excite an appreciable quantity of the K radiations of these elements.

Lithium, carbon, oxygen and boron

If elements of atomic number less than that of aluminum are bombarded, they might be expected to give the K radiation with large intensity. However the K radiations in these cases would be too soft to reach the ionization chamber. When the 2.38 million volt ions were made to bombard targets of lithium carbonate and boric acid, no radiation could be detected. It is believed that the K radiations were excited but were too soft to be observed.

Bromine

The bromine L radiation, unlike that of nickel and copper, is sufficiently hard (8A) to penetrate the window of the tube. The most prominent lines of the spectrum have wave-lengths of 8.36A, 8.34A, and 8.11A. The weighted mean is 8.3A. The target used was sodium bromide fused on to nickel. The sodium K radiation is quite soft (12A) and apparently was absorbed by the window. At any rate, it would be impossible to confuse the sodium and bromine radiations. Fig. 2 shows the absorption measurements. (The scale of abscissae is different from that for the other data.) The straight line has the slope corresponding to the absorption coefficient for 8.3A. It is seen that the points fit the line quite well. The measurements in air gave a mass absorption coefficient of 1000, whereas the value for 8.3A is 1050. There is little doubt but that the bromine L radiation was actually observed.

Molybdenum

The interpretation of the molybdenum results is complicated by the fact that the mercury M radiation has wave-lengths near those of the molybdenum L radiation. The possibility of exciting the mercury radiation must be considered since every collision in the target involves a mercury ion as well as a target atom. The strongest lines in the mercury M spectrum have wave-lengths of: 5.6, 5.4 and 5.0A. The weighted mean is 5.5A. In Fig. 2 a line has been drawn for this wave-length, as well as for 5.3A, the effective wave-length of the molybdenum L radiation. It is not possible to decide whether the experimental points fit the molybdenum curve or the mercury curve. It is even possible that both types of radiation were present. The intensity of the radiation from molybdenum was less than that from bromine. This fact is consistent with the hypothesis that the molybdenum L radiation was observed. The molybdenum L radiation requires more excitation energy than the bromine L radiation and would therefore be expected to have less intensity under the same conditions. With alpha-particle excitation, such is found to be the case.[5]

Silver and tin

The absorption data for silver and for tin are given in Fig. 2. The straight lines are merely those fitting the data best. These lines indicate, respectively, wave-lengths of 4.8 and 4.7A. The L radiations are at 4.0 and 3.5A, respectively. The significance of these results is not clear. Further investigation of these substances will be necessary.

Lead

The absorption measurements for the radiation from a lead target are shown in Fig. 2. The

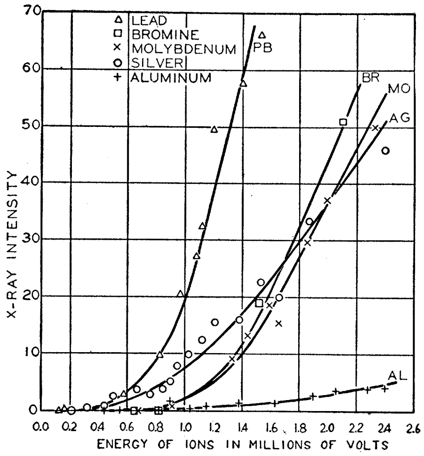

FIG. 3. Excitation curves.

straight line is that for 5.0A, the weighted mean of the wave-lengths of the lead *M* spectrum. The points lie nearer this line than the one for mercury. However it is not possible to say whether the radiation observed was the lead *M* radiation, or the mercury *M* radiation, or a mixture of both. The intensity from lead was greater than that from any other target—about four times that from molybdenum (see Fig. 3).

THE VARIATION IN X-RAY INTENSITY WITH THE ENERGY OF THE IONS

Excitation curves are plotted in Fig. 3 for five targets: aluminum, bromine, molybdenum, silver and lead. The abscissae represent the energy of the mercury ions as measured by the electrostatic field required to deflect them through a known angle. The ordinates represent the x-ray intensity as measured by the ionization chamber in arbitrary units. All of the data have been corrected for the absorption of the window. If the x-ray intensity were expressed in number of quanta, the aluminum and bromine ordinates would be increased by a factor of approximately 1.57. The other curves would be affected only very slightly.

It is at once obvious that the energy of the mercury ions has a marked influence on the x-ray intensity. The fact that the intensity is zero or too small to measure at energies less than 300 kilovolts no doubt explains why this type of radiation has not been observed before. Somewhat similar curves are found for the x-rays excited by alpha-particles.[5]

The curves seem to fall into three groups: aluminum—small intensity; silver, molybdenum and bromine—medium intensity; and, lead—large intensity. It is of interest to note that the radiation in the first group was apparently the *K* radiation, in the second group apparently the *L* radiation, and in the third group the *M* radiation. In particular, aluminum and bromine have very nearly the same effective wave-length for their *K* and *L* spectra, respectively. Hence the difference in intensity for these two elements indicates the difference in excitation probability for the *K* and *L* spectra.

AN ESTIMATE OF THE EFFICIENCY OF THE EXCITATION PROCESS

It is of interest to determine how many x-ray quanta are excited by a given number of mercury ions. It was not possible to determine this quantity accurately due to uncertainties as to the efficiency of the ionization chamber, the absorption of the radiation in the target, etc. The result should be regarded as a lower limit, since it was assumed that the ionization chamber absorbed the x-rays completely and that no x-rays were absorbed in the target. The calculation was made for the silver target, bombarded by 2.38 million volt ions so as to produce 2600 volt x-rays. The result shows that at least one quantum is produced for every 2000 mercury ions striking the target. The results of Bothe and Fränz show that alpha-particles are of the order of 1000 times as efficient as the mercury ions.[5] It was also found that the 2.38 million volt ions produced about ten times as many x-rays as did 3800 volt electrons striking the same target (molybdenum). These electrons were used since they produced x-rays of approximately the same average hardness as did the beam of ions.

EVIDENCE FOR SOFTER RADIATION

The experimental results have shown that *K*, *L* and *M* radiations were excited in various targets. Still softer radiation should also be excited. For example, the *L* radiation of aluminum should have been excited as well as the *K* radiation. The absorption of the window makes it impossible to observe such soft radiation with the ionization chamber. However such radiation should give rise to a noticeable photoelectric effect.

To investigate this possibility, the electrometer was connected to the brass grid which supports the mica window (Fig. 1). The remaining parts of the collector including the target were made 45 volts positive. When the target was bombarded by 2.38 million volt ions, a current indicating positive charges reaching the grid was observed. This current was about one-third of that to the target. The current seems too large to be due entirely to scattered ions, especially since it was nearly the same for an aluminum target as for a lead target. It is much more probable that the greater part of this current was due to photoelectrons ejected by very soft x-rays. If the observed effect were all due to photoelectrons the results would indicate about ten photoelectrons per mercury ion (over the whole solid angle), and of course many more x-ray quanta.

Another indication of the presence of very soft radiation was obtained when the ions were allowed to fall on an ordinary Eastman Kodak film. An intense blackening was produced after 30 seconds exposure to a current of 1×10^{-9} amperes of 2.38 million volt ions. It is not believed that the ions were able to penetrate the layer of gelatin which covers the emulsion in this type of film since the ions were found to be unable to penetrate the thinnest gold leaf available to the author (0.05 cm air equivalent). Hence the blackening must have been due to radiation excited by the ions, rather than to the ions themselves.

Discussion of the Results

The results obtained indicate that electrons have been ejected from the inner atomic shells as a result of mercury ion impacts. It seems probable that the process of excitation is somewhat as follows. Since the mercury ions have very large kinetic energies, the nuclei of the ion and the atom which it strikes sometimes approach very closely, and thus form essentially a molecule. Calculations show that the approach is in some cases so close that, for example, in the case of lead the M shells of the two atoms overlap. Hence, for a time, some of the M electrons are as near one nucleus as the other. When the molecule breaks up, it is possible that the M electrons will not be properly divided between the two nuclei, but that one nucleus will have one or more empty M levels. Hence M radiation must occur. It is obvious that either the target atom or the mercury atom might be excited. Similar considerations apply to the L and K shells of lighter atoms.

It is possible to calculate the minimum energy that a mercury ion must have in order to approach another atom closely enough to form such a quasi-molecule. The radius of the electron shells is given approximately by the Bohr theory. The distance of closest approach for a given energy is obtained by assuming a Coulomb repulsion between the two nuclei and taking into account the screening action of the electrons. From these considerations one readily obtains the following relation:

$$Z_1Z_2/x = V/300e(1+m_1/m_2),$$

where Z_1 and Z_2 are the effective atomic numbers of mercury and the target atom, m_1 and m_2 the respective masses, x the distance of closest approach (for a head-on collision), and V the energy of the mercury ion expressed in volts. To test the proposed theory, one may substitute for V the value of the experimental threshold of the excitation curve (Fig. 3) for each case, and for x the distance of approach which causes overlapping of the electron shells. A value for the effective atomic number may then be calculated. If the value proves to be of the right order of magnitude, the theory proposed will have been shown to be a possible explanation of the results.

Since there are two atomic numbers Z_1 and Z_2, the case of mercury ions striking lead atoms may be considered, where Z_1 and Z_2 can be assumed equal. The resulting value for Z_1 can then be used as the effective atomic number for mercury in the other cases. The distance x for this case is 1.53×10^{-9} cm. The threshold of the lead excitation curve (Fig. 3) gives the value 400,000 volts for V. The resulting value for Z_1 and Z_2 is 46.3, which seems quite reasonable since the effective atomic number varies from 1 at great distances of separation to 54 at the closest approach. If the calculated value is considered too high, it may be decreased by requiring that the two nuclei approach more closely in order to cause excitation, or by assuming that the true threshold is somewhat lower than that observed experimentally.

In the case of molybdenum, the distance x proves to be 1.22×10^{-9} cm. For Z_1 the value 51 may be taken. A value larger than 46.3 is chosen because the two nuclei approach more closely in this case. Using 700,000 volts for the threshold, one obtains for Z_2 a value of 37, which is too high, since the maximum value is 32. However, if it is assumed that the two nuclei must approach to a distance of 1.0×10^{-9} cm, and that the true threshold is 600,000 volts, the value of Z_2 becomes 26, which is quite reasonable.

In the case of the aluminum K radiation, if the threshold is taken as 500,000 volts, Z_2 becomes 9.2. Since the maximum value of Z_2 is 11, the calculated value is not unreasonable.

In view of the agreement between the experimental results and the theoretical calculations, it seems possible that the theory is essentially correct. It would seem that either the true thresholds are somewhat lower than the experimental ones, or that the two nuclei must approach somewhat more closely than originally postulated. This difference is of the order of 20 percent at most.

The author takes pleasure in expressing his gratitude to Professor Ernest O. Lawrence, who suggested this problem and directed the work on it, for his constant interest and many helpful suggestions. The author is also greatly indebted to Mr. David H. Sloan for assistance in connection with the production of the high speed ions.