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Recent Advances in the Production of Heavy High Speed Ions Without the Use of High Voltages

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A description is given of improvements in the Sloan-Lawrence method of accelerating heavy ions. The new apparatus yields mercury ions with energies of 2,850,000 electron volts, while the previous apparatus yielded ions with energies of 1,260,000 electron volts. The intensity of the beam of ions is of the order of 10^{-8} amperes—only slightly less than in the previous tube which was considerably shorter. The new tube withstands the application of 79,000 volts while the previous tube was limited to 42,000 volts. This improvement is due principally to decreased heating of the electrodes as a result of lowering their resistance and capacity. The spacing of the electrodes has been increased to 20 percent of their length, and their diameter decreased from 13 mm to 6 mm. The number has been increased from 30 to 36 and the length of each is now 25 percent greater. The possibility of extending this method to the acceleration of lighter ions is discussed.

INTRODUCTION

IN previous papers by one of the authors and E. O. Lawrence,[1] an apparatus which produced mercury ions having kinetic energies up to 1,260,000 electron volts was described. The method required the use of no potentials higher than 42,000 volts due to the fact that the ions were made to fall through this potential difference 30 times. Recently, further improvements including the building of a larger tube have made it possible to produce mercury ions with energies of 2,850,000 electron volts.[2] In this case only 79,000 volts is applied to the tube and the ions fall through this potential difference 36 times. The present paper is an account of the changes which have made possible this extension of the method. Another paper will describe some of the properties of these high speed ions.

[1] Sloan and Lawrence, Phys. Rev. **38**, 2021 (1931); Lawrence and Sloan, Proc. Nat. Acad. Sci. **17**, 64 (1931).

[2] A brief account of this work was presented at the Pasadena meeting of the American Physical Society, Phys. Rev. **43**, 212 (1933).

THE METHOD OF ACCELERATING THE IONS

Since the method of accelerating the ions has been described in previous papers,[1] only a brief account will be given here. The apparatus is shown schematically in Fig. 1. The ions travel through a series of copper tubes, or "accelerators," which are connected alternately to the opposite ends of the inductance of an oscillatory circuit. At any instant, there are electric fields of opposite direction and equal magnitude between successive accelerators. If an ion finds itself between the first and second accelerators, it will be drawn into the second accelerator provided that the field is in the right direction. If the proper voltage has been applied, the time consumed while the ion passes through this tube will be exactly one half period of the oscillations. Hence, the ion will arrive between the second and third tubes with the field reversed in direction, so that the ion will receive an additional acceleration into the third tube. Obviously each tube should have a length equal to the square

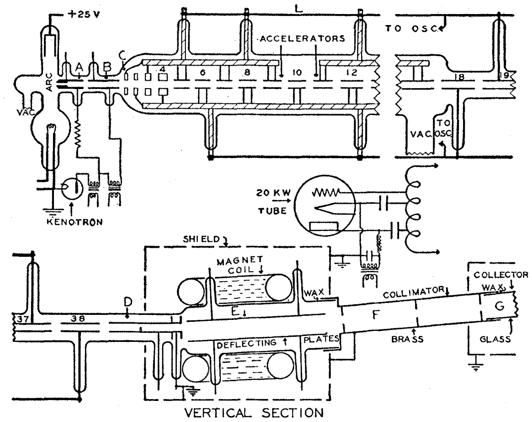

FIG. 1. Diagram of tube and oscillator circuit.

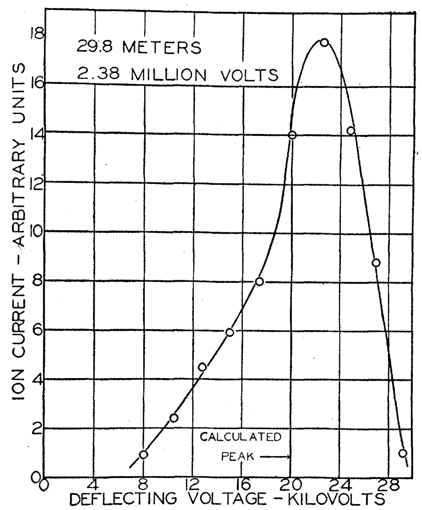

FIG. 2. Variation of ion current to collector with deflecting voltage.

root of its number in the series times the length of the first one (diminished so as to leave a gap between tubes) if each tube is to be traversed in a half period. Under these conditions, the ion will move through the series of accelerators in synchronism with the oscillating fields, gaining between each pair of accelerators an increase in kinetic energy corresponding to the applied voltage. For any given frequency of oscillation, there will be a voltage which gives synchronism between the moving ions and the oscillating fields. Thus, with the tube used in this work, oscillations at 29.8 meters require an applied potential of 79,000 volts and these conditions produce ions with final energies of 2,850,000 electron volts.

The final energy of the ions can be determined in three ways. It is equal to the average voltage between accelerators times the number of accelerators. (An average voltage must be used because the voltage changes while the ions are between accelerators.) Also, the final energy of the ions may be calculated from the period of the oscillations. The ions must of course pass through any accelerator in exactly one half period. Thus, the velocity (and hence the energy) may be calculated from the distance and time involved. Finally, the energy may be calculated from the value of the electrostatic field required to deflect the moving ions through a known angle. (See Fig. 1—*E* and *F*.)

The results of these three calculations are found always to be in quite satisfactory agreement. Fig. 2 shows a plot of the current of ions to the collector as a function of the deflecting voltage. (The collector, not shown in Fig. 1, is simply a Faraday cage.) The curve was taken for a frequency corresponding to 2.38 million electron volts. The deflecting voltage calculated for ions of this energy is 20 kv. It is seen that the peak of the curve is at a deflecting voltage about 10 percent higher. This result may indicate an error in measuring the angle of deflection. However, it is quite possible that the majority of the ions had more energy than that calculated from the frequency. The loading coil, which is inserted at *L* (Fig. 1) in order to increase the voltage on the first few accelerators, had only approximately the correct value when the data of Fig. 2 were taken. As has been pointed out in the previous paper of Sloan and Lawrence,[1] a loading coil which is too small may result in ions with energies in excess of the calculated value. At any rate, there can be no doubt but that the ions had at least the calculated energy of 2.38 million electron volts.

The width of the peak in Fig. 2 is rather great. This width is due partly to fairly wide slits in the collimator (Fig. 1—*F*), and partly to the presence of ions of more than one energy. This matter also has been discussed by Sloan and Lawrence. As they point out, the loading coil has an important effect on the width of the peak. It is quite possible that the peak could have been made sharper if that had been necessary.

The Present Experimental Arrangement

The present tube does not differ greatly in any one respect from the one previously described, but due to a number of small changes it is able to produce much faster ions. The principal changes were made in the accelerating system. The ion source, deflecting system, and pumping arrangements have not been modified in any important way.

The fundamental advantage of the new tube is that higher voltages can be applied to it (79,000 volts as compared to 49,000). The principal reason for this difference is the decreased heating of the electrodes due to decreasing the capacity and the resistance of the accelerator system. Also the gap between accelerators has been increased to 20 percent of the distance between their centers, except in the case of the first ten which are so short that the gap must be considerably more than 20 percent of their length. Another reason for the tube's ability to withstand higher voltages lies in the addition of two liquid air cooled glass bulbs which project into the region near the accelerators.

The accelerators in the new tube have been made 25 percent longer, thus allowing the ions to attain a higher velocity for the same frequency. The number has been increased from 30 to 36. As a result of these two changes the accelerating system is 185 cm long instead of 114 cm in the previous tube. The increased length makes the capacity greater, but this increase is more than offset by the increased spacing of the accelerators and by a reduction in their diameters. The tubes, formerly 13 mm in diameter, are now only 6 mm in diameter. In spite of this last change, the intensity of the beam is of the order of 10^{-8} ampere, and it appears that the focussing action is so strong that the present tube is as effective as the earlier one.

The electrical efficiency of the oscillatory circuit has been considerably improved by reducing the resistance of the connections between accelerators. The inductance coil was made of quarter inch copper tubing and arranged so as to have cooling water running through it. As a result of the increased efficiency it was possible to obtain 2.85 million volt ions with less than 10 kw input. In the previous tube, the same power produced only 1.26 million volt ions. The voltage applied to the tube is obtained from a Hartley circuit as described in the previous papers.

The design of the glass part of the tube seems worthy of mention. As shown in the figure, the first part of the tube was made of Pyrex glass four inches in diameter, while the latter part was made of two inch Pyrex tubing with each accelerator individually supported. The latter type of construction is simpler than the former and in operation, the smaller diameter part of the tube behaved in every way as well as the other part. When the accelerators are individually supported it is a simple matter to add more of them, and it is also possible to insert loading coils wherever desired. For these reasons it would be desirable to use the latter type of construction for the whole tube, except for the first few very short accelerators required in the case of the heavier ions.

Discussion

While this method of accelerating charged particles has so far been used only for mercury ions, it could readily be used for other ions. Lighter ions would travel faster for the same energy in proportion to the inverse square root of their masses. Nitrogen molecule ions (N_2^+) would travel somewhat less than three times as fast as mercury ions. The frequency of oscillation cannot be increased much over that so far used. It is, however, perfectly possible to make the accelerators longer, and in this case two and a half times the present length would be ample.

If the same number of accelerators were used, the tube would be two and a half times as long as at present. Such a tube could be operated by three oscillator tubes in parallel with a master oscillator to excite the grids. If, however, only one oscillator were used, as in the present work, the number of accelerators need not be reduced to less than twenty to leave the tube with the same length as at present, since the accelerators discarded are the long ones at the end of the series. With the smaller number of accelerators, the capacity would be less, so that higher 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.

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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

[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.