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Focused Beam Source of Hydrogen and Helium Ions*

G. W. Scott, Jr.
*Department of Physics, Cornell University, Ithaca, New York***

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An ion source of high intensity is described in which the ions are produced by bombarding a region of gas by a focused beam of electrons. This ion source is universal in that it may be used with any gas that may be ionized by electron impact. A theoretical expression for the emission from the ring-shaped cathode used in this source is given, and the emission *vs.* voltage curve calculated from this expression is compared with experimental emission curves. Electron beams as intense as 2.2 amp./cm^2 are reported. Curves of total ion yield from the source plotted against (1) electron emission (2) electron energy (3) pressure are presented. Hydrogen ion beams of four ma are reported. The difficulty of focusing an ion beam of high intensity is discussed. A mass spectroscopic analysis of hydrogen and helium ion beams is presented. The proton yields vary from five percent to 80 percent of the total hydrogen ion beam and are seen to be a function of pressure, electron energy, and electron emission. The He^{++} yield in the helium ion beam is of the order of five percent of the total beam current.

1. Introduction

In the ion source described in this paper, the ions are produced by bombarding gas atoms with a focused beam of electrons. With the guidance of the analysis of Smith and Scott,[1] which specifies the minimum potential required for complete removal of the ions formed by electron impact, this type of ion source offers a good opportunity to obtain conveniently intense beams of a wide variety of ions. Several ion sources of this type[2,3] have been built, and, the source to be described represents the simplest and most convenient modification to date.

2. Description of Ion Source and Auxiliary Apparatus

The constructional details of the ion source are drawn to scale in Fig. 1. The ionization chamber assembly G is made from a copper rod one inch in diameter. The actual chamber is a cylindrical hole $\frac{1}{4}''$ in diameter and $\frac{3}{8}''$ deep in the end of the copper rod. Gas is introduced into and directed toward the back of the ionization chamber by means of two 13-mil holes shown in Fig. 1. The flow is regulated by a gas leak described by Fowler,[4] placed between the ionization gauge and the Hoke reducing valve attached to the tank containing the gas to be ionized. The entire ionization chamber assembly is water cooled by a pipe which introduces water into the central portion of the copper rod and by another pipe surrounding and coaxial with the first, which removes it.

The cathode D is of 15-mil oxide-coated, protruded nickel, cylindrically shaped, mounted coaxial with the ionization chamber and $\frac{1}{16}''$ from it. It is spot-welded to 15-mil nickel strips which are attached to the lead-ins as shown in Fig. 1. The cathode is coated with type 50 oxide spray coating, manufactured by Callite Products Company, Union City, New Jersey.

Figure 2 is a diagram of the electrical connections. The pumping system is an all metal, three-stage, self-purifying, condensation pump, employing Eastman's octoil as the pumping medium. The details of construction and important characteristics of this pump are described by Malter and Marcuvitz.[5] According to Malter and Marcuvitz, the speed of this pump varies from 35 to 40 liters/sec. over a pressure range from 10^{-3} to 10^{-6} mm Hg. From measurements made in this work, it was found that to maintain a pressure of 5×10^{-5} mm Hg at the ionization gauge, a gas flow of approximately eight cc/hour, measured at atmospheric pressure,

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* Part of a thesis submitted by G. W. Scott, Jr., in partial fulfillment of the requirements for the Ph.D. degree in the graduate school of Cornell University.

** Now at Massachusetts Institute of Technology.

[1] L. P. Smith and G. W. Scott, Jr., preceding paper.

[2] L. P. Smith and G. W. Scott, Jr., Phys. Rev. **51**, 1025(A) (1937).

[3] L. P. Smith and G. W. Scott, Jr., Phys. Rev. **53**, 677(A) (1938).

[4] R. D. Fowler, Rev. Sci. Inst. **6**, 26 (1935).

[5] L. Malter and W. Marcuvitz, Rev. Sci. Inst. **9**, 92 (1938).

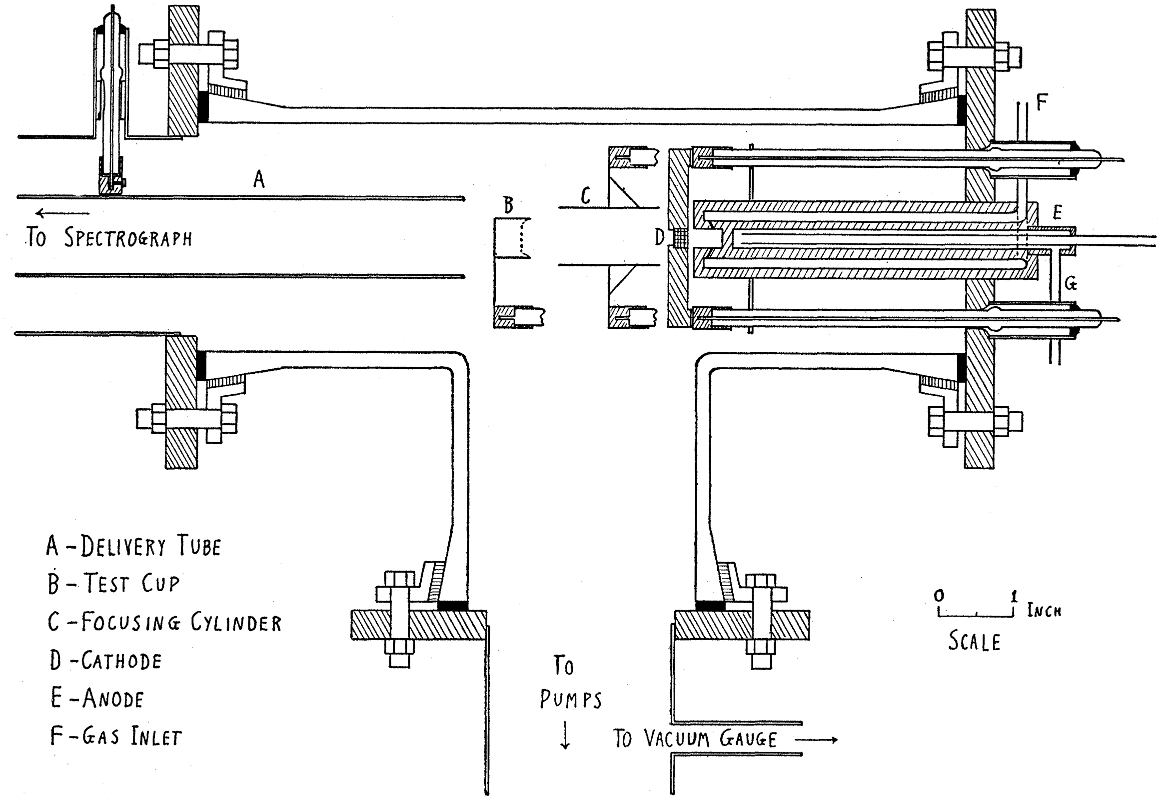

FIG. 1. Ion source assembly. *A*-copper focusing cylinder, *B*-test cup mounted so that it may be turned into or out of the ion beam. A willemite screen makes the ion beam visible. *C*-nickel focusing cylinder, *D*-cylindrical cathode $\frac{1}{4}''$ in diameter and 5/32″ wide coaxial with beam, *E*-copper-anode assembly with ionization chamber, gas inlet *F*, and water cooling *G*.

is required; whereas to maintain a pressure of 5×10^{-4} mm Hg at the ionization gauge a gas flow of approximately 57 cc/hour, measured at atmospheric pressure, is required.

3. Electron Production

Necessarily a very important feature of the type of ion source being discussed is the production of intense beams of electrons. The cathode construction and coating have already been described.

In Fig. 3 are plotted the currents between anode and cathode for two pressures of hydrogen as functions of anode-cathode voltage. The dashed curve is a plot of $i=Ci_0^{\frac{1}{2}}V^{3/4}$ (i is cathode emission, i_0 is saturation current density, C is a constant) which an approximate theoretical calculation gives for the thermionic emission of this type of cathode when the positive ion space charge is neglected. The effect of the positive ion space charge is clearly evident. Cathodes of satisfactorily long life have produced electron beams of 600 ma (2.2 amp./cm^2) with not more than 800 volts anode-cathode potential and 12 to 13 amperes heating current.

4. Total Ion Yields

The positive ion yield as a function of electron emission current for constant electron energy and hydrogen pressure is shown in Fig. 4. Since under these circumstances the ionization produced by an electron beam is directly proportional to the number of electrons in the beam the points of this curve should fall on a straight line as they do. In Fig. 4 is also shown the way in which the ion current varies with electron energy when the emission and pressure are kept constant. This curve has the general shape to be expected from the variation of cross section for ionization with electron energy. However, the

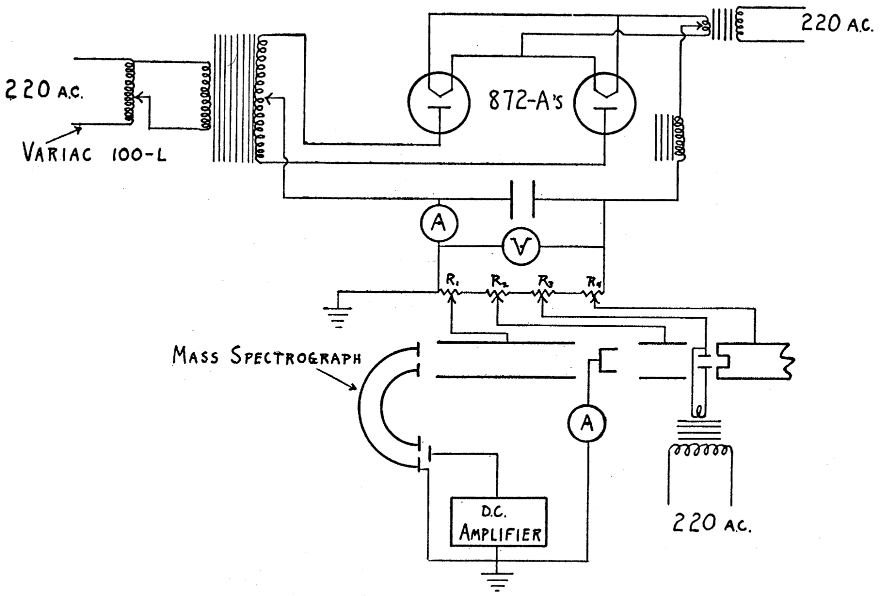

Fig. 2. Schematic diagram of apparatus and electrical connections. R_1, R_2, R_3 and R_4 are 2000-ohm, 1000-watt variable resistors. The power transformer will dissipate 3 kw (3000 v at 1 amp.).

maximum of the curve comes at a somewhat higher potential than for the ionization cross section curve. This is probably due to the fact that not all the positive ions are drawn out of the ionization chamber at the lower potentials. The variation of the total ion current with pressure at constant electron emission and energy is shown in the curve of Fig. 5. This curve has a point of inflection whose interpretation is interesting. As the pressure is increased the ion current would be expected to increase somewhat faster than a first power law because of the contribution of multiple collisions and secondary electrons. This is observed to be the case. However, after the point of inflection, it increases slower than a first power law. Such a change of slope may be attributed to the fact that after the pressure has reached a particular value, more ions are formed than the potential available will remove and so a part of them necessarily flow to the walls of the ionization chamber.

Focused ion beams as high as four ma have been measured to the test cup. For a four-ma hydrogen ion beam, the hydrogen pressure at the ionization gauge was 3×10^{-4} mm Hg, the electron emission 500 ma, and the test cup biased 90 volts positive to hold secondary electrons. A theoretical estimate[1] of the optimum ion yield under these conditions gives 4.8 ma. Total helium ion yields are somewhat less, since the ionization cross section for helium is less than that for hydrogen.

5. Focusing of the Ion Beam

In this source, the focusing of ion and electron beams is accomplished by the electrostatic fields between configurations of coaxial cylinders. At the higher intensities the focusing is made more difficult by the positive space charge in the beam which tends to make it diverge.

For total ion intensities up to 100 μa the ion beam responded readily to the focusing fields. In a typical instance the ionization chamber was 1250 volts above ground, the cathode 750 volts, and the auxiliary focusing cylinder at ground. The ion current was measured to a cup biased positively to hold in secondary electrons, enclosed in a grounded shield box with a $\frac{3}{8}''$ opening. The current to the cup responded to variations in the potential on the focusing cylinder, indicating that the beam reaching the cup was a focused beam.

The highest ion beam focused to the test cup

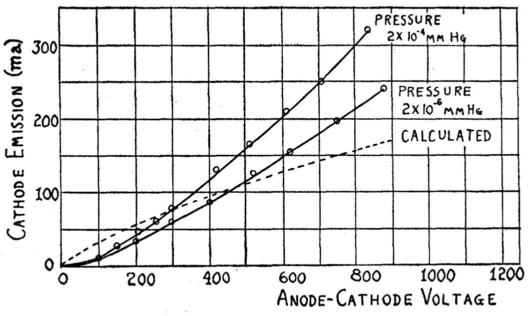

FIG. 3. Theoretical (dashed curve) and actual cathode-anode current as a function of anode-cathode voltage.

has been a four-ma hydrogen ion beam, but in this case the focusing was not complete. The ionization chamber was 3000 volts above ground and the cathode 2200 volts above ground. The focusing cylinder was placed at the same potential as the cathode, acting in the capacity of guard ring to the latter. The ion delivery tube was at ground potential, while the test cup to which the four-ma ion beam was measured was biased 90 volts positive to hold in the secondary electrons. In the case of the high intensity ion beams it is possible to observe how complete the focusing action is by the glow produced by the ion beam.

6. MASS SPECTROSCOPIC ANALYSIS OF THE ION BEAM

Figures 6 and 7 give mass-spectrograph curves of the ion beam for hydrogen pressures (1) 1×10^{-5} mm Hg and (2) 8×10^{-5} mm Hg, which show the variation of the beam content as a function of pressure. It is to be emphasized that the pressure reading is always at the ionization gauge, whose location may be seen from Fig. 1, and not in the ionization chamber. The beam in Fig. 6 is seen to be composed entirely of H_1^+ and H_2^+, the proton yield being 48.5 percent of the total beam current. The beam in Fig. 7 contains not only H_1^+ and H_2^+ but also H_3^+ and all of the breakup products[6] H_{3-1}^+, H_{3-2}^+, H_{2-1}^+. The proton yield in this instance is 13.1 percent.

It will be concluded from the above date that the proton percentage in the hydrogen ion beam is definitely a function of the pressure. As a matter of fact, the proton yield under varying conditions has been observed to range from five percent to 80 percent. In general when the total ion yield is 100 μa or less, experience has shown that one may expect the proton yield to be approximately 50 percent. Such a wide observed variation in the proton yields has made it seem worth while to take a careful set of relative abundance measurements in hydrogen as a function of pressure, electron energy and electron emission in an attempt to determine what are the variables of which the proton yield is a function. In Table I, column (a) gives proton yields calculated on the basis of only the products H_1^+, H_2^+, H_3^+, whereas in column (b) the yields are calculated on the basis of the three products above and all the breakup products appearing in a particular instance. From the data in Table I, as well as the mass-spectrograph curves of Figs. 6 and 7, it is apparent that the proton percentage is a function of the pressure, decreasing from a

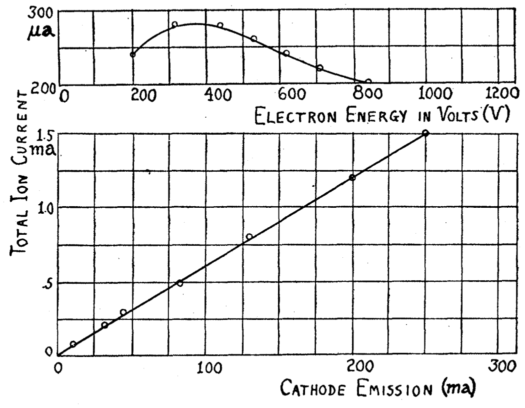

FIG. 4. Total hydrogen ion current as a function of bombarding electron current and variation of total ion current with energy of bombarding electrons with pressure constant.

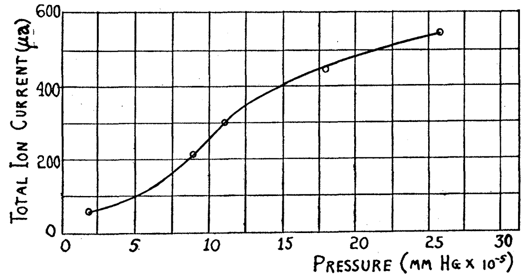

FIG. 5. Variation in total ion current with hydrogen pressure-electron current constant.

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[6] H. D. Smyth, J. Frank. Inst. 198, 795 (1924).

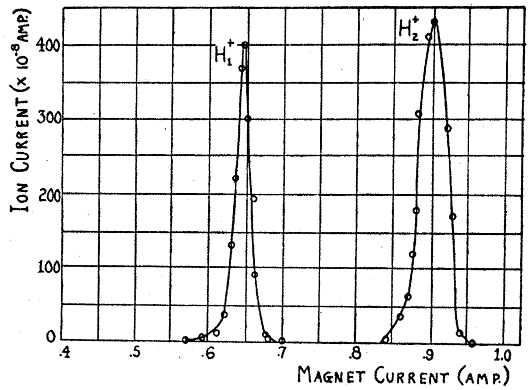

FIG. 6. Mass-spectrographic analysis of ion beam for $p=1\times10^{-5}$ mm Hg.

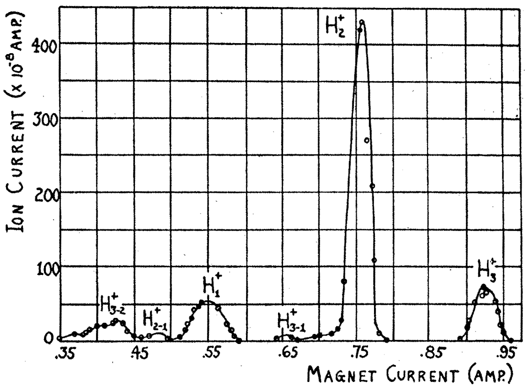

FIG. 7. Mass-spectrographic analysis of ion beam for $p=8\times10^{-5}$ mm Hg.

high value at low pressure to as low as five percent for high pressure. Although the variation is not as obvious as in the case of the pressure, the proton yield is seen to be a function of both the electron energy and the electron emission. For low pressures, the proton yield decreases as the energy of the electrons increases, whereas for high pressures the yield increases with an increase in electron energy. Again at low pressures the proton yield varies approximately as the square root of the electron emission, while at higher pressures there is no apparent change with variation in the electron emission. This is in accord with the theoretical relation (4a) derived by Smith and Scott.[1] The high proton yields observed compare favorably with those of other workers,[7] and appear to be brought about by low pressure and high electron density.

The agreement with the theoretical relation mentioned above leads one to believe that the important processes involved in the formation of protons in the sources under consideration are

$$\begin{aligned} &H_2+e\rightarrow H_1+H_1+e \\ &H_1+e\rightarrow H_1^{+}+2e \end{aligned} \qquad (1)$$

$$H_2+e\rightarrow H_1^{+}+H_1+2e \qquad (2)$$

and possibly

$$\begin{aligned} &H_2+e\rightarrow H_2^{+}+2e \\ &H_2^{+}+H_2\rightarrow H_3^{+}+H_1 \\ &H_1+e\rightarrow H_1+2e. \end{aligned} \qquad (3)$$

These processes have all been observed experimentally by other workers.[8] Although Hughes

TABLE I. *Proton yields.*

Hydrogen Pressure (mm Hg)	Electron Energy (volts)	Electron Current (ma)	(a) Proton Yield Without Breakup Products	(b) Proton Yield With Breakup Products
1×10^{-5}	400	125	61.2%	53.8%
	500		58.0	52.0
	600		57.3	52.7
	400	90	56.1	48.6
	500		51.8	45.8
	600		50.9	46.2
	400	60	47.6	47.6
	500		48.4	43.4
	600		58.5	54.2
3×10^{-5}	400	125	12.1	15.7
	500		14.1	16.7
	600		17.3	20.0
	400	90	14.1	16.7
	500		13.9	16.9
	600		16.0	18.1
	400	60	14.1	16.7
	500		17.5	19.5
	600		26.1	27.7
7×10^{-5}	400	125	5.7	10.4
	500		5.2	10.8
	600		12.4	15.9
	400	90	6.1	10.2
	500		6.1	9.15
	600		10.2	13.4
	400	60	4.9	9.4
	500		6.0	9.9
	600		9.8	13.5

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[7] E. S. Lamar, W. W. Beuchner and K. T. Compton, Phys. Rev. **51**, 936 (1937).

[8] N. F. Mott and H. S. W. Massey, *Theory of Atomic Collisions* (Oxford University Press, 1933), p. 215.

and Skellett[9] have reported the probability of process (1) to be low, with the very high intensity electron beams employed in this work the likelihood of the H_1's liberated in the process being ionized before recombination takes place is good. This is especially true at low pressure. Consequently, process (1) may be responsible for the observed high proton yields at low pressure and high electron intensity.

An analysis of the helium ion beam with the mass spectrograph showed the yield of He^{++} to be of the order of five percent of the total ion beam.

The author wishes to acknowledge the assistance he has received in this work from Professor L. P. Smith and Dr. P. L. Hartman.

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[9] A. L. Hughes and A. M. Skellett, Phys. Rev. **30**, 11 (1927).

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On Radiative Corrections for Electron Scattering

S. M. Dancoff
University of California, Berkeley, California

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A relativistic treatment of the radiative correction of order $e^2/\hbar c$ to the elastic scattering cross section leads to the following results: (a) For the scattering in an electrostatic field of a particle described by the Pauli-Weisskopf theory, the correction is finite and is given by (3). (b) For the scattering of a Dirac electron in an electrostatic field, the correction diverges logarithmically and is positive. (c) The convergence or divergence of the correction depends critically on the type of scattering potential considered.

THE customary quantum-mechanical treatment of the scattering of electrons in a field of force involves the assumption that radiative reaction may be considered a small correction. However, when one attempts to calculate the contribution of radiative effects to the scattering cross section, certain characteristic difficulties are encountered.[1] Making an expansion in powers of $\alpha = e^2/\hbar c$, one finds that the probability of scattering with emission of a single quantum with frequency between q and $q+dq$ behaves as dq/q at low frequencies, resulting in an infinite cross section. This "infrared catastrophe" has been shown to arise from the illegitimate neglect, implied in the expansion, of processes involving the simultaneous emission of many light quanta. By taking these into account, and considering only frequencies so low that the light quantum energy and momentum may be neglected in comparison with those of the electron, one finds, in complete analogy with the classical result, that the scattering probability is just that which is obtained by neglecting radiative effects entirely.

If we now consider the contribution of higher frequencies we might expect to find that as the light quantum energy is increased, a point is reached beyond which the expansion in powers of α is legitimate; this would imply the convergence at high frequencies of the successive terms in the expansion. The first-order terms in α are of two types, one giving the cross section for scattering with emission of a quantum, the other giving a correction to the elastic scattering cross section. For light quantum energies higher than the electron's kinetic energy, the radiative cross section vanishes and only the correction to elastic scattering remains. It is with the behavior of this correction for high light quantum energies that we shall be concerned.

According to Braunbek and Weinmann, if one takes a point charge for the electron and neglects

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[1] N. F. Mott, Proc. Camb. Phil. Soc. **27**, 255 (1931); F. Bloch and A. Nordsieck, Phys. Rev. **52**, 54 (1937); W. Braunbek and E. Weinmann, Zeits. f. Physik **110**, 360 (1938); W. Pauli and M. Fierz, Nuovo Cim. xv, 3, 1 (1938).