molecular field the coupling is broken down and replaced by separate λ-quantization in the configuration $2p\sigma(2p\pi)^3\,{}^3\Pi$($2p\sigma$ is the promoted H electron). In this case a_{MH} may be compared with a_{M} of a $2p$ electron in the N atom as observed in the state $(2s)^2(2p)^2 3s\ {}^2P$. The calculation on this basis made by Mulliken for NH and PH can be refined with the more accurate determinations of the molecular coefficients,[4] and the case of OH^+ included. The results are in Table IV. The value for OH^+ supports the assumption that the OH^+ bands are analogous to the NH and PH bands.

No comparison of coupling coefficients for a $\sigma\pi$ configuration seems to have been made. The ${}^3\Pi$ states of BH and AlH provide such a case. Following Mulliken we put $a_{\mathrm{MH}}=2A$ and $a_{\mathrm{M}}=(2/3)\Delta\nu$ where $\Delta\nu$ is the doublet interval in the ${}^2P$ state from which the molecular ${}^3\Pi$ is derived. $a_{\mathrm{MH}}/a_{\mathrm{M}}$ is greater than one for both molecules. This calculation, however, supposes the molecular splitting to be due entirely to the ls interaction of the $p\pi$ electron and neglects the interaction of l of $p\pi$ with the spin of the $p\sigma$ electron.

JUNE 1, 1937 PHYSICAL REVIEW VOLUME 51

Low Voltage Proton Sources*

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(Received February 27, 1937)

Further experiments have been carried out with a view towards increasing the proton percentage obtainable from capillary arc sources previously described. The collision method of breaking up molecular ions has been investigated. Although no difficulty was experienced in refocusing the scattered ions, no evidence was found for break-up in the absence of magnetic fields. Rather than investigate these possibilities further, a quartz capillary was tried, using a simple beveled outlet. This eliminated the rapid disintegration of the quartz by secondary electrons from any probe electrode, but there was still evidence of gradual disintegration of the quartz by low speed electrons in the discharge. The absence of excessive heating indicated that the capillary might as easily be made of Pyrex. A Pyrex capillary source was therefore tried. In a 3.5 mm capillary, heating was not excessive at arc currents below 0.3 ampere. The proton percentages ranged up to 20 percent. Following the experience of Wood, water vapor was introduced, and resulted in a marked increase in the proton percentage (a factor of about 4). This source possesses the advantages of slightly greater ion current efficiency, requires no cooling, is easily constructed, and is free from impurities.

Introduction

In view of the rapidly increasing number of high voltage installations for nuclear research, it has become desirable to develop more adequate sources of positive ions, particularly protons. Since, in most of these installations, both space and total power output are limited, the ideal source should require a minimum of space and power. To this end, the fraction of the total gas flow which is ionized should be as high as possible to minimize the pumping requirements. In addition, artificial cooling should not be required, since this would necessitate auxiliary equipment. The source should give high ion purity, so that the available power will not be wasted in accelerating objectionable ions. The source described by Lamar and Luhr[1] possesses the advantage of high ion purity and requires no cooling. Its successful operation, however, necessitates extreme care in experimental technique. Moreover, the current densities obtainable are small. The capillary type ion source,[2, 3] although giving high ion current density, requires cooling, and does not give high ion purity. The object of the present investigation has been to reduce the discrepancies between the ideal source and the present existing types.

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[*] A preliminary report of this work was presented at the Washington Meeting of the American Physical Society, May, 1936.

[1] Lamar and Luhr, Phys. Rev. **46**, 87 (1934).

[2] Tuve, Dahl and Hafstad, Phys. Rev. **48**, 241 (1935).

[3] Lamar, Samson and Compton, Phys. Rev. **48**, 886 (1935).

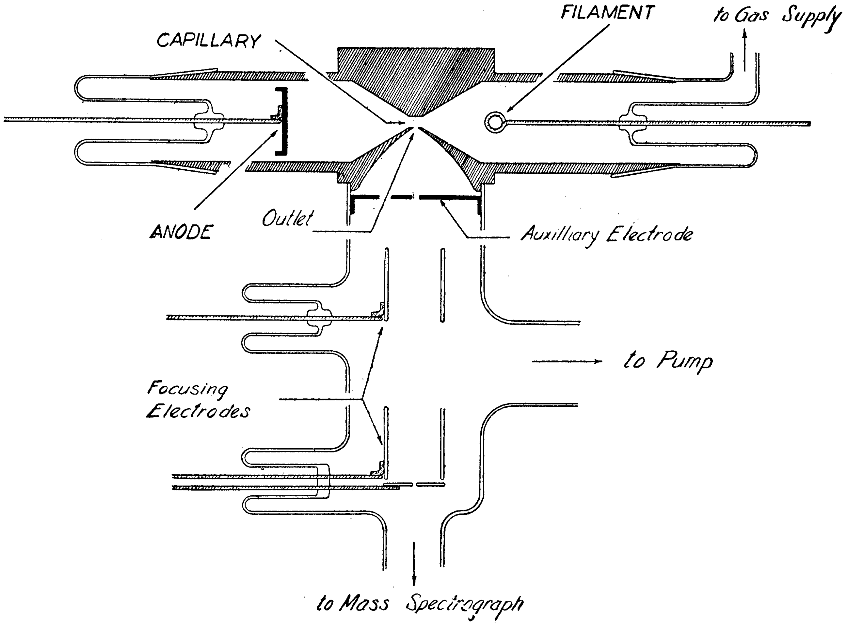

FIG. 1. Metal capillary source showing break-up electrode.

METAL CAPILLARY SOURCES

In the work of Lamar, Samson and Compton,[3] some hope for increased proton percentages was offered by the fact that heavy ions at high speeds break up, on collision with gas molecules, into protons and neutral particles. This effect had been observed previously by Smyth[4] and others. In the paper mentioned above in the third reference, a tentative design for a break-up chamber was proposed. Following this suggestion, such a chamber was built. A diagram of the experimental arrangement is shown in Fig. 1. The source itself was exactly the same as the one previously described. The enclosing wall for the break-up chamber consisted of a metal plate, with a central hole 3 mm in diameter. The potential of this plate could be controlled independently of the other circuit elements. It was found that, with increasing voltages, more and more of the total output of the source could be focused through the hole, until at 5800 volts, 60 percent of the total output was realized. The pressure in the chamber could be varied by varying the pressure in the arc. In the paper mentioned in the third reference, limits were set on the efficiencies of ion break-up, the upper limit agreeing in order of magnitude with that calculated by Smyth. In the present work, the pressure in the break-up chamber was kept sufficiently high to insure the number of collisions required on the basis of these efficiency calculations. The fraction of the current getting through the hole did not depend to any marked degree upon the pressure in the chamber.

The ions were focused into a mass spectrograph for analysis. Various arrangements of accelerating potentials were tried. Although peaks in the mass-spectrograph curves were found identifiable as broken up ions, in every case they corresponded with ions which had fallen through the entire potential difference. They were, therefore, ions which were produced by break-up in the region immediately above the spectrograph, and not in the break-up chamber. Since the solid angle subtended by the slit of the spectrograph at the hole in the plate was small, it was believed at first that the apparent absence of broken up ions from the chamber was due to small angle scattering in the chamber. In order to refocus these scattered ions, the potential between the plate and the lower electrodes was made large in comparison with the potential

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[4] H. D. Smyth, Phys. Rev. 25, 452 (1925).

between plate and source. The failure to observe broken up ions from the chamber under these conditions indicated that the process did not take place in the break-up chamber. Considerable care was exercised in the establishment of this negative result. To quote a particular set of experiments, with 1000 volts on the break-up electrode and 5000 volts over-all, primary protons plus protons resulting from break-up were expected, ranging in voltage between 4300 and 5000. The width of the proton peak measured in units of magnet current should then have 7.1 percent of the magnet current at the peak. The observed width, even at pressures in the source as high as 0.55 mm, was only 5 percent, which is approximately the resolving power of the spectrograph. Furthermore, an increase in the ratio of proton current to H_3^+ current was expected, but not observed. The possibility that these protons appeared as a highly spread background was ruled out by the fact that the background was less than 0.2 percent of the height of the H_3^+ peak. The only apparent difference between the break-up chamber and the region immediately above the spectrograph was the presence of a stray magnetic field in the latter. Hence, it would appear that ion break-up, although a collision process, for voltages below 5000 volts, takes place only in the presence of a magnetic field. This rather surprising indication, although interesting as a subject for further research, seems less promising at present than other possibilities for the development of an improved ion source.

A significant result of the experiments with the break-up chamber was the lack of difficulty experienced in the refocusing of the ions scattered in the high pressure region. If one is interested in high total ion currents, one is faced with the necessity of handling large gas flows. To do this in a single pumping stage requires an extremely fast system. The flow of gas into the main high voltage tube, however, can be reduced appreciably by differential pumping from the high pressure region formed by the introduction of the additional electrode. For the particular case of the tube shown in Fig. 1, one may calculate from the geometry what decrease in gas leakage one may expect with intermediate pumping. Pumping through the annular ring separating the electrode from the source, one might hope to gain a factor of the order of 100 in reduction of gas leakage, since the ratio of the areas of the hole and the ring is 200. Since, for electrode potentials as low as 5800 volts, 60 percent of the ion current from the source was focused through the hole, the above calculation represents a gain in available ion current, for a given gas leakage, of a factor of approximately 100. Suitable design with this in mind could be made to give even higher factors of gain, particularly since, at 5800 volts, the indications were that higher voltages would focus a larger fraction of the current.

QUARTZ CAPILLARY SOURCE

Rather than investigate the break-up mechanism further, a source was constructed having the capillary of quartz. Quartz capillary sources had been tried previously by Mohler and by Tuve and his collaborators. In their sources, rapid disintegration of the quartz resulted from bombardment by secondary electrons from the high voltage probe used for drawing the ions out of the arc. Since, in our case, a simple beveled hole was used as an outlet, allowing the ions to drift out into the nearly field free space of relatively high vacuum in the discharge tube before attempting to focus them into a beam, it was hoped that this disintegration would be avoided. Furthermore, it was believed that the clean quartz surfaces would be less effective as a catalyst for the recombination of atomic hydrogen than the metal or the disintegrated quartz surfaces in the sources that had been tried previously. This source is shown in Fig. 2.

Mass-spectrograph analysis of the ions obtained with this source, however, showed a proton percentage little or no better than that obtained from the metal sources. In addition, investigation of the capillary after some hours of use showed a gradual disintegration of the quartz, presumably by low speed electrons in the discharge. In operation, there was no apparent overheating of the capillary, indicating that the source might as easily be made of Pyrex, with the attendant elimination of graded seals and other inconveniences connected with the use of quartz.

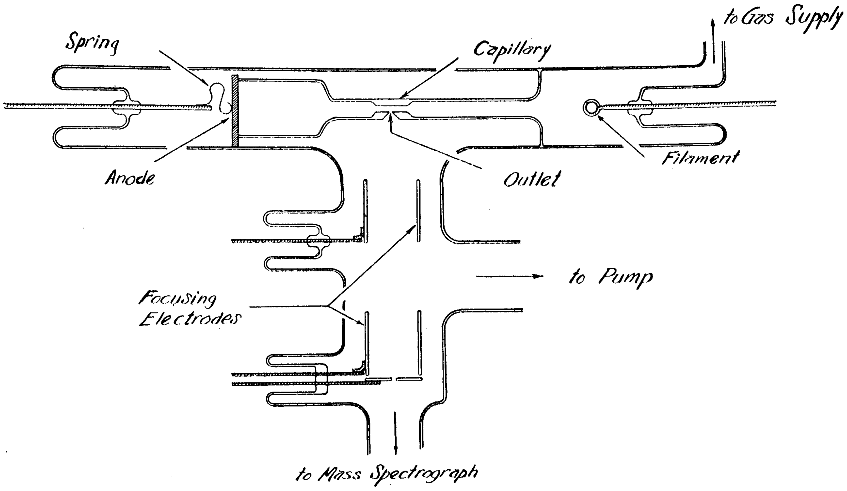

FIG. 2. Typical nonmetal capillary source.

PYREX CAPILLARY SOURCE

A Pyrex capillary source was constructed, therefore, in the manner indicated in Fig. 2. For the 3.5 mm diameter capillary used, no undue heating of the capillary occurred for arc currents below 0.3 amp. The spectrum of the discharge was viewed through a transmission grating, and was predominantly that of atomic hydrogen up to arc currents of 0.3 amp., above which the atomic spectrum increased in intensity along with the appearance of the sodium D lines, indicating that the capillary was beginning to overheat. With this source, proton percentages were found ranging up to 20 percent. Following the experience of Wood, water vapor was introduced into the tube, in an attempt to increase the atomic hydrogen present in the discharge. This resulted in a marked increase in the intensity of the atomic spectrum. It might be of interest to remark in passing that it was feared that the water vapor might have a deleterious effect upon the oxide coated filament used for a cathode. It was found, however, that, instead of being harmed by the water, the filament actually seemed benefited by its presence. This, of course, is contrary to usual experience with gases other than hydrogen. The water vapor was introduced into the discharge by having saturation vapor pressure in the hydrogen reservoir, the percentage of water vapor used being controlled by varying the hydrogen pressure. Typical mass-spectrograph curves taken with this source are shown in Fig. 3. The bottom curve shows the beam constitution with no water vapor in the source, and it is seen that the protons amount to about 18 percent of the total ion current. The middle curve was taken with a hydrogen pressure in the reservoir of 4 cm, the arc pressure being 0.04 mm. It is seen that the proton percentage in this case has increased to approximately 58 percent. The top curve was taken at an arc pressure of 0.18 mm, and here the proton percentage is 80 percent. No attempt was made to increase this last figure, but it is probable that further adjustment of the water vapor concentration would allow even higher percentages. A search was made for water vapor and for atomic oxygen ions, and none were found. It was not convenient to look for molecular oxygen ions. However, the lack of water vapor ions, atomic oxygen ions, and the purity of the atomic hydrogen spectrum make it improbable that any molecular oxygen ions were present.

It was found that the source operated quite satisfactorily using hollow cathodes made of stainless steel, a potential of approximately 600 volts being necessary for an arc current of 0.2 ampere. The power input for a given arc current is, of course, increased by the amount of the increase in cathode fall. In particular, the total arc drop with a hot cathode was approximately 150 volts, deviating from this value slightly with changes in pressure; whereas, with the hollow cathode, the total arc drop for the same current was about 600 volts. With a hot cathode, the arc was quite stable at pressures as low as 0.04 mm; whereas, with a hollow cathode, it was difficult to maintain a discharge at pressures below 0.2 mm. This minimum could be reduced, of course, by increasing the dimensions of the hollow cathode, since the indications are that the minimum pressure at which a hollow cathode will operate depends upon its diameter measured in mean free paths. The hollow cathode used in

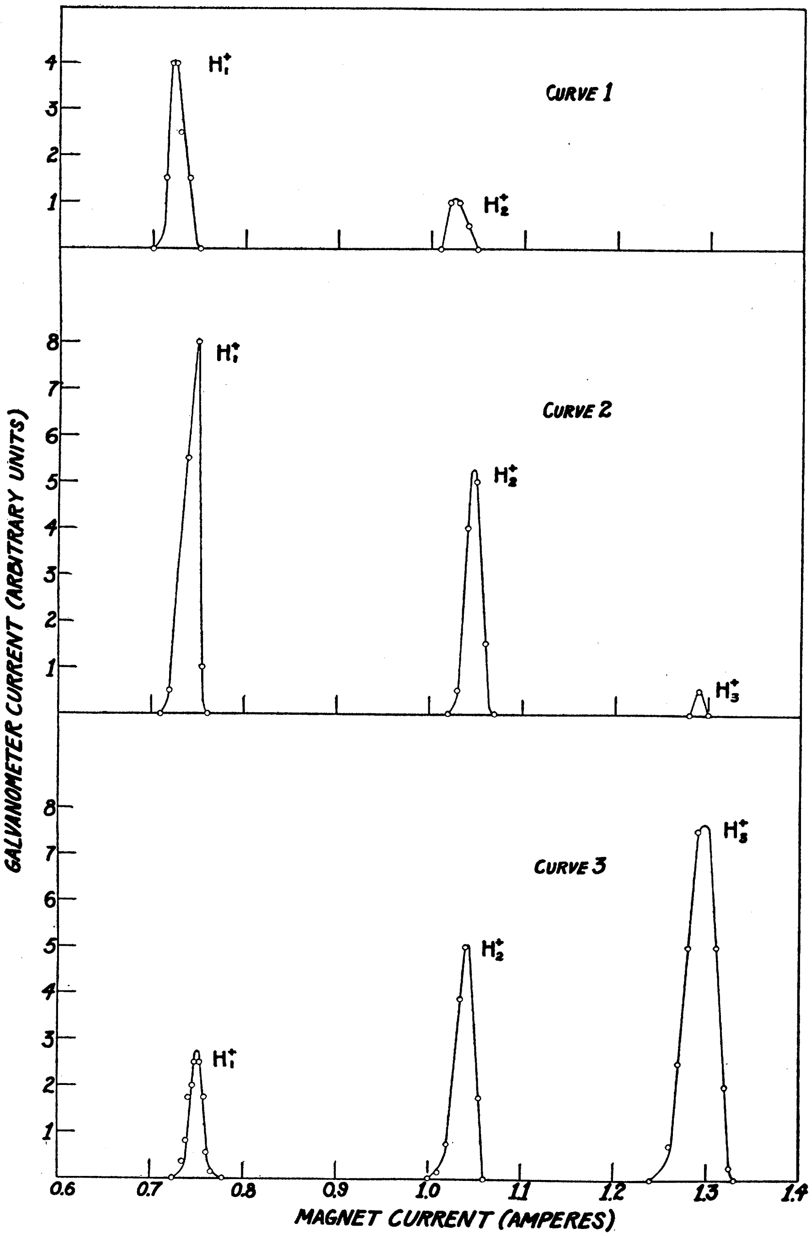

FIG. 3. Mass-spectrograph curves for Pyrex capillary source. Curve 1: Arc pressure of 0.18 mm, arc current 0.2 amperes, 30 percent water vapor in reservoir. Curve 2: Arc pressure 0.04 mm, arc current 0.2 ampere, 45 percent water vapor in reservoir. Curve 3: Typical curve with no water vapor in reservoir.

TABLE I. *Typical performances of M. I. T. proton sources. A is the source utilizing accommodation coefficients to achieve high percentage of hydrogen dissociation. B is metal capillary source with hydrogen. C is the Pyrex source with moist hydrogen.*

	A	*B*	*C*
Pressure in arc	0.23–0.60 mm	0.04–0.49 mm	0.04–0.45 mm
Arc current	1.00 amp.	0.1–5 amp.	0.1–0.3 amp.
Total power used	61–97 watts	60–550 watts	68–101 watts
Ion current density	1.4–10.5 milliamps/cm^2	7–1000 milliamps/cm^2	21–46 milliamps/cm^2
Percentage of protons	98–100*%	5–20%	58–80%
Percent useful ionization†	0.0021–0.04%	0.0003–2.21%	0.012–0.41%

† The percent useful ionization is the ratio of the number of protons to the number of gas molecules leaving the outlet per second expressed in percent.
* Lower values if metal surfaces are not clean.

these experiments was already one inch in diameter. It seems out of the question, therefore, to hope to better this by another order of magnitude.

In the Pyrex source, ion currents of 60 microamperes were obtained with an arc current of 0.2 ampere in a 3.5 mm capillary with an outlet hole 0.5 mm in diameter. With the Pyrex source, as with the metal source, the ion current per unit effective outlet area is proportional to total arc current, as is described in detail in the third reference. For a given outlet area, the ion current per unit arc current in the case of the Pyrex source is slightly in excess of that reported for the metal source. Heating of the Pyrex capillary limits the arc current in the present source to 0.3 ampere. This limitation is partly compensated for by the increased ion purity. The presence of insulating, rather than conducting, walls makes for ease of starting and stability of operation. Since the ion current obtainable is adequate for most requirements, and since it requires no cooling, this source compares favorably with other types, even in its present form. Obviously, the direction in which to seek improvement lies in providing some convenient means for cooling the capillary. This might be accomplished by first coating the capillary with some conducting film, such as Aquadag, and then depositing, by means of electroplating, a heavy coating of copper, thus providing a low resistance path for the flow of heat away from the capillary.

In conclusion, a rough comparison between the sources tested at M. I. T. is given by Table I.

The authors wish to acknowledge their indebtedness to Dr. C. M. Van Atta for helpful advice and criticism.