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ELECTRIC DISSOCIATION OF H^+ IONS BY MAGNETIC FIELDS

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ABSTRACT

Electric $\vec{v} \times \vec{B}$ dissociation of H^- ions moving through a magnetic field has been measured for electric field strengths near 2 MV/cm. The H^- ions were obtained by charge exchange of protons in water vapour and were accelerated to 49.5 MeV by the proton linear accelerator at the Rutherford High Energy Laboratory. Stripped particles were detected using an acoustic spark-chamber. Experimental lifetimes are lower by approximately a factor of two from those predicted by Mullen ¹⁾ and a factor of three from those predicted by Hiskes ²⁾. Our measurements also appear inconsistent with those of Cahill *et al.* ³⁾

ELECTRIC DISSOCIATION OF H^- IONS BY MAGNETIC FIELDS

1. Introduction

Four universities in Western Canada[†] have formed a consortium called TRIUMF to build a 500 MeV variable energy, sector-focussed H^- cyclotron on the University of British Columbia campus. The accelerator, based on the UCLA meson factory proposal by Richardson,⁴⁾ utilizes negative hydrogen ions to achieve the variable energy feature and almost 100 per cent extraction efficiency. The design calls for 100 μA of extracted protons.

Of crucial importance to the design of the accelerator magnet is the lifetime of the H^- ions in the magnetic field. The binding energy of the second electron is only 0.755 eV. This bond can be broken by the electric field (or Lorentz force) which results from the motion of the ion in the magnetic field. Explicitly, the equivalent electric field in the rest frame of the H^- ion is given by

$$\epsilon = 0.3 \beta \gamma B \times 10^6 \text{ volts/cm}$$

where $\beta = v/c$, $\gamma = (1 - \beta^2)^{-\frac{1}{2}}$, v is the velocity of the ion,
and B = the magnetic field in kilogauss.

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Simon Fraser University

Too large a value of the magnetic field for a given ion velocity would cause premature stripping of the loosely bound electron resulting in a loss of beam intensity, excessive radiation levels during machine operation, and high residual activation of the accelerator.

Gas stripping by the residual gases in the vacuum vessel also contributes to beam losses, but mainly at low ion energies. This process has been studied extensively ⁵⁾ and will not be treated here.

Experimental determinations of the lifetimes of negative ions in magnetic fields have been made. Kaplan *et al.* ⁶⁾ observed complete electric dissociation of the D^- ions at an electric field strength of about 4.2 MV/cm. Cahill *et al.* ³⁾ determined the lifetimes of H^- ions at electric field strengths from 2.2 to 2.4 MV/cm. In addition, several theoretical investigations of the lifetime of the H^- ion for electric dissociation have been carried out ^{1,2,7-10)}. Of these, the calculations of Mullen ¹⁾ and of Hiskes ²⁾ are in best agreement with the experimental data of Cahill *et al.* ³⁾. The mean lifetimes predicted by these two theories are shown in fig. 1 together with the experimental data of Cahill *et al.* ³⁾.

The range of interest for TRIUMF is for electric fields of 2.1 MV/cm to 1.8 MV/cm corresponding to approximately 500 MeV and 400 MeV H^- ions respectively in the peak field of approximately 6 kg contemplated for TRIUMF. To minimize magnet and shielding costs and to keep the residual activity of the machine to a tolerable level, a better knowledge is required of the H^- lifetimes in this range than can be obtained from the existing data or

theories. The purpose of this experiment was to obtain this knowledge. Accurate data on the electric dissociation is also of interest to test the various theories of this process.

2. Experimental Method

2.1 GENERAL

Our measurements were made at the Rutherford High Energy Laboratory using the 50 MeV proton linear accelerator. A schematic view of the experimental arrangement is shown in fig. 2. The H^- beam was obtained by passing the 500 keV protons from the Cockroft-Walton injector through a gas electron-adder canal located between the injector and the first accelerating tank. This canal was 25 cm long and contained water vapour at a pressure of approximately 200 microns. Liquid nitrogen traps at each end of the canal prevented leakage of water vapour into the accelerator. After acceleration to 49.5 ± 0.1 MeV, the proton and H^- beams were separated by an analyzing magnet, the protons being dumped in a concrete cave at the end of the $+15^\circ$ beam line while the H^- ions were focussed into the "stripping" magnet at the end of the -15° beam line.

The H^- ions entered the "stripping" magnet through a series of baffles in the vacuum vessel. These baffles allowed maintenance of a pressure differential between the beam line ($\sim 6 \times 10^{-6}$ torr) and the stripping region ($\sim 2 \times 10^{-7}$ torr). After passage through the stripping field, the deflected H^- beam was detected by a fast counter-telescope. H^0 atoms present in the beam at the entrance to this field were monitored with a

similar telescope. Gas-stripped and electric-stripped H^- ions were detected by a position sensitive acoustic spark chamber triggered by a ΔE -E particle identification system¹¹⁾. The magnet and the detection systems are discussed in more detail in the following sections.

The average H^- counting rate at the detector plane 107 cm from the magnet centre was $10^5/\text{sec}$. This corresponds to an instantaneous rate of $\sim 10^7/\text{sec}$ since the linear accelerator duty factor is 1%. An overall view of the experimental apparatus is shown in fig. 3.

2.2 MAGNET AND MAGNETIC FIELD MEASUREMENTS

The stripping field was provided by a modified Type I Nimrod[†] magnet. New pole pieces 17.8 cm wide by 50.8 cm long were made to provide a 6.35 cm gap. Trim coils were connected in series with the main magnet coils to provide a field profile which was as uniform as possible in the region of the pole faces and which dropped sharply beyond them. This arrangement was capable of producing a peak field of 23 kg at a magnet current of 500 amperes. However, because of limitations on the size of the stripping vacuum vessel, the useable peak field for experimental purposes was about 21.8 kg.

Magnetic field measurements were made with a Hall probe calibrated against an NMR probe. An extensive survey of field profiles at several magnet currents was made prior to the experiment. Following the experiment,

[†]The 7 GeV proton accelerator at R.H.E.L.

the field was checked with an NMR probe and agreement to ± 15 gauss was obtained.

Shown in fig. 4 are diagrams of the magnet pole pieces together with typical measured field profiles. The profile measurements showed that the field was within 1% of peak field over ± 3 cm in the y-direction, ± 8 cm in the x-direction and ± 1.3 cm in the z-direction. (The coordinate system is defined in fig. 4.)

The position of the vacuum vessel relative to the magnet poles is shown in fig. 5. To facilitate the trajectory calculations, the y-axis was shifted 10 cm from the geometric centre of the stripping magnet so that the "straight-through" H^0 beam passes through the origin of the coordinate system. The computed trajectories of the H^- ions in fields of 21.44 and 20.55 kg are shown in fig. 5.

2.3 DETECTORS AND ASSOCIATED ELECTRONICS

The deflected H^- beam was monitored by a fast counter telescope consisting of two 56AVP phototubes and 0.32 cm thick NE102A plastic scintillators. An auxiliary power supply was used on the last three dynodes of each tube to maintain a constant voltage on them at high count rates. A resolving time of 8 nsec with a dead time of 21 nsec was used. Since the H^- counting rate (10^5 /sec average) is near the upper working limit for this type of detector, the beam intensity was also checked with an argon-methane ionization chamber. This chamber was positioned in front of the counter telescope and the ion current produced by the beam was compared to the

counting rate in the telescope. An electrometer was used to measure the ion current, and a conversion factor ¹²⁾ of $(1.96/P) \times 10^{-8}$ amperes per 10^8 protons/sec was used to convert the electrometer reading to protons per second (P is the gas pressure in atmospheres).

Two ion chamber gas pressures were used for this test: 1/20 of an atmosphere and 1 atmosphere. Two typical measurements yielded beam currents of 1.8×10^5 and 2.0×10^5 protons/sec for the lower and higher gas pressures respectively. The corresponding telescope rates, corrected for dead time losses, were 1.9×10^5 and 2.1×10^5 protons/sec. Thus, the two methods of measuring the beam current were consistent to approximately five per cent. Large angle scattering of the beam by the ion chamber was found to be negligible by repeating the measurements with the chamber positioned behind the telescope.

A similar telescope was used to monitor the "straight-through" H^0 beam. The ratio of detected H^0 atoms to detected H^- ions was approximately 10^{-2} .

The H^- ions electrically (or gas) stripped in the magnetic field were detected by a position-sensitive sonic spark chamber and particle identification system which was developed by Swales ¹¹⁾ for the use with the $n_{\frac{1}{2}}$ magnetic spectrometer at the PLA laboratory. The spark chamber had an effective active volume of dimensions 40 cm long, 3.2 cm wide and 0.48 cm deep. A microphone was mounted at one end of the chamber to pick up the acoustic signal from the spark discharge. A 50 per cent saturated ethanol-argon gas mixture was passed through the spark chamber continuously.

A particle identification system located immediately behind the spark chamber pulsed a voltage of 9 kV across the chamber electrodes (windows) whenever an event of interest occurred. A small clearing potential was applied continuously across the electrodes, and the time delays were set so that the high voltage was applied just before the electron column from the ion track was completely cleared. In this way good spark localization was achieved.

The particle identification system consisted of two scintillation detectors, a transmission or ΔE detector followed by a full energy or E detector operating in coincidence ($2\tau = 20$ nsec). The ΔE detector was a 50 cm long by 10 cm wide sheet of 0.32 cm thick NE102A plastic scintillator mounted in a light tight box at an angle of 45° with respect to the horizontal and viewed from above along its length by three 56AVP photomultipliers. The E detector was similar except that the scintillator was 1.9 cm thick and was mounted vertically. It was also viewed by three 56AVP photomultipliers. The detector arrangement is shown in fig. 3. Electronic windows were set around the peaks in the ΔE and E spectra corresponding to the 49.5 MeV beam particles.

In addition to this restriction, the spark chamber was allowed to trigger only once per beam burst. Since the maximum counting rate in the spark chamber during the experiment was 5×10^{-2} counts per beam burst, a negligible number of counts was lost due to this restriction.

The position of the spark in the chamber was determined by measuring the time delay between the detection of a particle of interest in the particle

identification system and the arrival of the acoustic pulse at the microphone. This was accomplished by means of a Laben 512 channel pulse-height analyzer with its own built-in time-to-amplitude converter. The stability and linearity of the "time-of-flight" spectrum depends on the constancy of the velocity of sound in the spark chamber. This was assured by maintaining the argon-ethanol gas at a constant temperature, pressure (atmospheric) and mixture composition using a gas handling system described by Swales ¹¹⁾. The calculated velocity of sound in the chamber is 3.1×10^4 cm/sec which gives a calibration of 0.12 cm per channel for the time-of-flight spectra for the time-to-amplitude conversion gain used. This and the linearity of the system were checked with a β -source. A spark chamber time-of-flight spectrum for a stripping field of 21.69 kg is shown in fig. 8.

3. Experimental Results

Horizontal and vertical profiles of the beam were taken with the spark chamber to ensure that the H^- beam was sufficiently well focussed on the detector plane. These are shown in fig. 6. The FWHM in each case is about 0.8 cm. The beam was also scanned along the length of the spark chamber in order to check its operation.

A run at low field (16.97 kg, where calculation showed that electric stripping should be negligible) was made in order to provide a measurement of gas-stripping mean life. The time-of-flight spectrum from the spark chamber is shown in fig. 7. The rise at the left of the distribution is due to the tail of the H^0 beam since, at this field, the H^- beam

was not deflected sufficiently far from the "straight-through" H^0 beam. These data correspond to an average background rate of 0.15 per channel per sec or 3.3 per channel per $10^6 H^-$ ions and, assuming gas stripping only, a mean life of $(700 \pm 30) \mu\text{sec}$. This value is consistent with that extrapolated from existing data ¹³⁾ for a pressure of approximately 5×10^{-7} torr of air. For this run, the pressure at the exit of vacuum vessel was 1.9×10^{-7} torr while that in the beam line in front of the baffles was 6×10^{-6} torr. The possibility of background arising from particles being scattered from the walls of the vacuum vessel into the spark chamber was investigated by allowing the beam to strike the vessel walls. No increase in background was observed.

The electric stripping for six different field settings from 18.94 kg to 21.69 kg was studied. The spark chamber spectrum obtained for a field of 21.69 kg is shown in fig. 8. The histogram was obtained by summing over four channel groups. The solid curve is that predicted from a computer code to be discussed later. The dashed line represents the background calculated from the measured gas-stripping cross section.

4. Data Analysis

Data obtained from the spark chamber was converted into electric-stripping lifetimes in two ways. One method--the "strip" method--considered a small slice at the centre of observed distribution. The other method--the "integral" method--used the entire observed distribution.

The "strip" method used information contained in 32 channels at the peak of the observed distribution. This portion of the spectrum corresponded to about 4 cm on the detector plane and to about 2 cm of the trajectory. These counts arose from H^- ions which were stripped either by gas or electric stripping during passage through the region of peak magnetic field. Over this portion of the trajectory, the equivalent electric field was constant to within 0.1% and thus could be considered uniform for purposes of analysis. Since the number of H^- ions stripped, $\Delta N(H^\circ)$, along the element of arc length, Δs , is small (approximately 10^{-5} H° per H^- per cm at 21.44 kg), then

$$\Delta N(H^\circ) = N_0(H^-)[1 - \exp(-t/\gamma\tau)] \sim N_0(H^-) \frac{t}{\gamma\tau} = N_0(H^-) \frac{\Delta s}{v\gamma\tau} \quad (1)$$

where $N_0(H^-)$ is the number of H^- ions in the incident beam, t is the time required by the ions to traverse the length Δs , v is their velocity, γ is the Lorentz factor, and τ is the mean life of an ion (in its own rest frame) in the magnetic field. From the observed numbers of counts in the strip and in the H^- telescope, the known velocity of the ions, and the calculated Δs , a mean life, τ_{exp} , was obtained for each value of the stripping field used. This mean life was used together with the experimental gas-stripping mean life, τ_g , to obtain an electric-stripping mean life, τ_e , from

$$\frac{1}{\tau_e} = \frac{1}{\tau_{\text{exp}}} - \frac{1}{\tau_g} \quad (2)$$

In the "integral" method the whole distribution was used in the analysis. The basis of this method lies in the following argument. The number of electric-stripped H^- ions along an element of trajectory ds is inversely proportional to their mean life in that element. Thus, from equation 1, it follows that the total number of electric-stripped ions is given by

$$N(H^-) \propto \int \frac{1}{\tau(\epsilon)} ds \quad (3)$$

If an expression for $\tau(\epsilon)$ is known (or assumed), the expected number of stripped ions can be calculated. Further, if the magnetic field profile is such that stripping occurs only in a small region, the mean life of the ion rapidly increases as the ion leaves the stripping region. A graph of the reciprocal of the mean life of the ion as a function of arc length will then be almost rectangular. We define, then, an equivalent constant field B^* (for which there is a corresponding constant mean life τ^*) of length s^* such that the same number of ions would be stripped in this field as in the actual non-uniform field. Then, the calculated number of stripped ions is

$$N_{\text{calc}} \propto \int \frac{1}{\tau(\epsilon)} ds \equiv s_{\text{calc}}^* \left[\frac{1}{\tau^*} \right]_{\text{calc}} \quad (4)$$

The choice of either s_{calc}^* or $\left[\frac{1}{\tau^*} \right]_{\text{calc}}$ is completely arbitrary but having chosen one of these quantities the other is uniquely determined.

Similarly, an s_{exp}^* and $[\frac{1}{\tau^*}]_{\text{exp}}$ can be defined for experimental data such that the observed number of electric-stripped H^- ions is given by

$$N_{\text{exp}} \propto \int \frac{1}{\tau(\epsilon)} ds \equiv s_{\text{exp}}^* [\frac{1}{\tau^*}]_{\text{exp}} . \quad (5)$$

Thus,

$$\frac{N_{\text{calc}}}{N_{\text{exp}}} = \frac{s_{\text{calc}}^*}{s_{\text{exp}}^*} [\frac{1}{\tau^*}]_{\text{calc}} [\frac{1}{\tau^*}]_{\text{exp}}^{-1} \quad (6)$$

or

$$[\frac{1}{\tau^*}]_{\text{exp}} = \frac{N_{\text{exp}}}{N_{\text{calc}}} \frac{s_{\text{calc}}^*}{s_{\text{exp}}^*} [\frac{1}{\tau^*}]_{\text{calc}} . \quad (7)$$

It is natural to choose $s_{\text{calc}}^* = s_{\text{exp}}^*$. Thus, an experimental electric-stripping mean li

$$[\frac{1}{\tau^*}]_{\text{exp}} = \frac{N_{\text{exp}}}{N_{\text{calc}}} [\frac{1}{\tau^*}]_{\text{calc}} . \quad (8)$$

$$[\frac{1}{\tau^*}]_{\text{exp}} = \frac{N_{\text{exp}}}{N_{\text{calc}}} [\frac{1}{\tau^*}]_{\text{calc}} . \quad (8)$$

The resulting values of $[\frac{1}{\tau^*}]_{\text{exp}}$ are used for a recomputation of N_{calc} . In practice, consistent consecutive values of $[\frac{1}{\tau^*}]_{\text{exp}}$ were obtained in two or three iterations using a function dependence for $\tau(\epsilon)$ of the form

$$\tau(\epsilon) = (A/\epsilon) \exp(B/\epsilon) \quad (9)$$

where A and B are constants. Initial values of $A = 1.05 \times 10^{-14}$ sec-MV/cm and $B = 49.25$ MV/cm (which correspond to Hiskes' prediction in fig. 1) were used.

In order to compare values of mean life obtained by these two methods, $[\frac{1}{\tau^*}]_{\text{calc}}$ was taken as the reciprocal of the minimum value of τ along the trajectory--that is, $[\frac{1}{\tau^*}]_{\text{calc}}$ corresponds to the reciprocal of the mean life at the maximum value of equivalent electric field that the ion encountered in its trajectory.

Each of these methods of analysis requires a calculation of the particle trajectory. The "strip" method requires this for the computation of arc length, while the "integral" method requires it for the calculation of the expected number of stripped ions. It should be mentioned that the integral method is independent of the linearity and the time calibration of the time-of-flight spectra.

A computer program was written which calculated the particle trajectory from the measured magnetic field profiles. The trajectory calculated from the horizontal centre line profile was used as a first approximation. The coordinates of that trajectory were used to compute a modified field profile using the measured field values. From this field profile a new trajectory was calculated. Four iterations were required before the ratio of the difference between the "old" x-coordinates and the "new" x-coordinates to the "new" x-coordinates was less than 10^{-5} . (Increments along the y-axis were fixed. See fig. 5 for a definition of

the coordinate system used.) Calculation of the x-coordinates was based on a method given by Coggeshall and Muskat¹⁴).

The trajectory computed for peak fields of 20.55 and 21.44 kg are shown in fig. 5. It was observed experimentally that, at the point of exit from the vacuum vessel, the H^- beam had undergone ≈ 2 cm less deflection in the + x-direction than that predicted by the computer code. The reason for this is that field profiles were measured to only 13 cm from the magnet centre line in the x-direction. For calculation purposes the profile at 13 cm was used for x-coordinates greater than 13 cm. Since the field along the line with $x = 13$ cm is larger than that further from the centre of the magnet, somewhat more deflection of the H^- beam will be predicted than will be observed. This does not affect the calculation of the expected number of stripped ions, however, because stripping does not occur in these fringe field regions; the position on the detector plane of the stripped distribution will, however, be shifted slightly to larger values of x. The predicted shape of the stripped H^- distribution shown in fig. 8 has been shifted to match the peak of the observed distribution. It can be seen in fig. 8 that the shape of the stripped H^- distribution is accurately reproduced by the calculation.

5. Discussion of Results

Table 1 lists the values of electric-stripping mean lifetimes obtained in this experiment. The column labelled "B" gives the value of the field at the centre of the magnet. Columns labelled " $B_{\max}$ " and " $\epsilon_{\max}$ " give,

respectively, the maximum values of magnetic field and corresponding electric field encountered by the ions during their traverse of the magnet. Mean lifetimes obtained by the "strip" and "integral" methods are shown in the appropriate columns. Figure 9 shows our results together with those of Cahill *et al.*³⁾ The insert shows the lifetime as predicted by Hiskes²⁾ and as obtained by the fit to our data in the region of electric field strengths near 4 MV/cm. The points 1 and 2 represent conditions under which Kaplan *et al.* observed no dissociation and complete dissociation respectively⁶⁾; loss by a factor of e would occur roughly at the point P. (This data has been taken from fig. 1 of ref. ¹⁰⁾.)

Errors quoted in our measurements for the "strip" method include those arising from uncertainty in the speed of the ion, calculation of arc length and statistical errors in the observed number of counts in the spark chamber and in the gas-stripping mean life. For the "integral" method the errors quoted arise from statistical uncertainty in the total number of stripped ions and from background subtraction. A correction (ranging from 10% to 40%) for dead time losses in the counter telescope is included in each calculation. No correction was included for the finite size of the H^- beam in the stripping field. This omission leads to additional uncertainty in the "strip" method, but not in the "integral" method. The agreement between the lifetimes determined by the two methods indicates that this effect was not important.

Our results are in disagreement with those predicted by the theories of Hiskes²⁾ and of Mullen¹⁾. Hiskes assigns an uncertainty of a factor

of three to his calculation which contains one adjustable parameter whose limits are not easily prescribed. Our data then lie near the lower limit of his prediction. The curve showing the prediction of Mullen ¹⁾ is based upon a more complete treatment. This treatment takes exact account of the barrier penetration effects and accurate account of the many electron effects by a method in which the H^- variational wave function is used to calculate a spectroscopic factor for the process. Therefore, this calculation is not subject to the arbitrary uncertainties of earlier treatments. However, as in the earlier treatments, this calculation does not take correct account of the geometry of the electric field. All the calculations have overestimated the lifetime by assuming that the electrons pass through the barrier in a straight line path rather than the actual curved path. This geometrical correction is currently being calculated and may bring the calculated lifetimes of Mullen ¹⁾ down to our measured values ¹⁵⁾.

At the present time our results appear to be inconsistent with those of Cahill *et al.* ³⁾. We can offer no explanation of this disagreement.

6. Acknowledgements

We would like to thank Professor W.D. Allen of the PLA Laboratories for making the machine available to us for these measurements. We are also very grateful to John Boon, Ted Wallis, John Macken, Frank Swales, Paul Reeve and the rest of the PLA staff for their invaluable help without which this experiment would never have been completed.

TABLE 1
Experimental Mean Lifetimes of H^- Ions in Magnetic Fields

Run	B (kg)	$B_{\max}$ (kg)	$\epsilon_{\max}$ (MV/cm)	"Strip" method* (μ sec)	"Integral" Method (μ sec)
9	18.96	18.92	1.867	424 $\pm$ 28	416 $\pm$ 52
26	19.39	19.36	1.910	218 $\pm$ 14	200 $\pm$ 22
23	20.06	20.03	1.976	84.8 $\pm$ 2.6	88.5 $\pm$ 2.8
13	20.55	20.53	2.025	54.3 $\pm$ 1.6	54.2 $\pm$ 1.3
24	21.44	21.43	2.114	20.1 $\pm$ 0.7	20.4 $\pm$ 0.5
7	21.44	21.43	2.114	22.3 $\pm$ 0.7	20.2 $\pm$ 0.4
14	21.69	21.69	2.140	16.0 $\pm$ 0.4	16.9 $\pm$ 0.4

* Calculated using gas-stripping mean life of $(700 \pm 30) \mu$ sec.

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Figure Captions

- Fig. 1. Experimental H^- mean lifetimes obtained from ref. 3. Theoretical predictions from refs. 1 and 2 are also shown.
- Fig. 2. Schematic view of the experimental arrangement. The position of the spark chamber is denoted by S/C. ΔE and E are the detectors of the particle identification system.
- Fig. 3. Photograph of the H^- experimental apparatus.
A. Magnet; B. Vacuum Vessel; C. Spark Chamber; D. ΔE Detector; E. E Detector; F. H^0 Telescope; G. H^- Telescope; H. Ion Pumps.
- Fig. 4. Magnet pole pieces and field profiles. The upper half of the figure shows the shape of the stripping magnet pole pieces and defines the coordinate system used for field measurement. Measured field profiles are shown in the lower portion of the figure.
- Fig. 5. The position of the stripping vacuum vessel and detectors relative to the position of the stripping magnet pole pieces. Also shown are calculated H^- trajectories at 21.44 and 20.55 kg and the coordinate system used for trajectory calculations.
- Fig. 6. Horizontal and vertical beam profiles as observed with the spark chamber.
- Fig. 7. Results of a background run at 16.97 kg. The rise at the left of the spectrum is due to the tail of the "straight-through" H^0 beam.

- Fig. 8. The observed spark chamber distribution of stripped H^- ions at a field of 21.69 kg. The solid curve is the profile predicted at this field by the computer program described in the text. The dashed line represents the background calculated from the measured gas-stripping cross section. The error bar shown in the upper left corner is typical of the statistical errors of points at the top of the distribution.
- Fig. 9. A comparison of present experimental data with that from ref. 3. Also shown are the theoretical predictions from refs. 1 and 2. The coefficients A and B of eq. 9 for the curve fitting the present data points are $A = 7.96 \times 10^{-14}$ sec-MV/cm and $B = 42.56$ MV/cm. For explanation of insert, see text.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9