NEGATIVE ION ACCELERATION AND RELATED MEASUREMENTS(*)

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(Presented by B.T. Wright)

Energy Gain Per Turn

A knowledge of the energy gain per turn is needed to evaluate various data. We obtained the value of the energy gain per turn as a function of radius by measuring the flight time of a beam pulse from the ion source to a given radius.

We found it possible to pulse a standard Oak Ridge type ion source by applying a fast voltage pulse from filament to ground. The ion source was first adjusted so that it ran stably with an arc voltage of 100 volts and an arc current of 2 amperes. Then the arc voltage was turned off, and a 300 volt pulse with a rise time of 0.5 μs was applied. Beam pulses with rise times (from 10% to 90%) of about 5 μs were obtained. The arc current pulses were found to have approximately the same rise time. By increasing the filament current and reducing the gas pressure, beam pulses with rise times of less than 3 μs could be obtained, Fig. 1 shows a typical negative-ion pulse.

We detected the negative-ion pulse by measuring the current due to stripped electrons left on a 0.1" copper foil (see Fig. 2 and 3). The instantaneous currents were as small as 10^{-9} A at times. To obtain a usable voltage signal we used a large input impedance (approximately, 1 megohm). This large input impedance, combined with the probe capacitance, gave a very slowly rising signal. This condition was improved by placing a coaxial cable inside the probe. The shield was driven by a unit-gain cathode follower such that the voltage on the shield was maintained at essentially the same voltage as that of the central conductor. In this way the effective capacitance was reduced by a factor of 50 to 100. The rise time of the probe-preamp combination was about 1 microsecond.

A signal from the arc pulse was used to trigger the delayed sweep on an oscilloscope, which was used to measure the arrival time of the beam pulses as a function of radius. Fig. 4 shows some measured flight times. The absolute flight time was not determined by these measurements because of the unknown amounts of delay in the various components. However, over most of the range of radii considered, the time differences could be determined to ± 0.25 microseconds. The beam energy was determined from the radius and the known magnetic field. The estimated accuracy of the energy gain per turn is ± 10%.

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A few comments on difficulties should be made. Occasionally, when the ion source was not properly positioned, a positive background current was observed on the stripper. The stripper probe shown in Fig. 3, minimized this difficulty. RF pickup on the bare stripper caused very little trouble because both the preamp and the plug-in amplifier used in the oscilloscope had band passes of 5Mc/s or less. The preamp was completely battery powered to eliminate RF pickup from power lines. Finally, because the oscillator was being pulsed, care was taken to pulse the arc on at the center of the oscillator pulse.

The instantaneous beam during a pulse was at times a factor of ten greater than the beam when the arc was operated in the normal manner.

Gas Stripping Measurements

We measured the total cross-section per atom of air for the stripping of electrons from negative hydrogen ions in the energy range 14-45 MeV.

As is described in more detail elsewhere, a probe was developed which measures the cyclotron circulating current by collecting the electrons stripped from negative ions. The probe current was determined before (I_1) and after (I_2) the admission of air to the cyclotron through a standard leak. Fig. 5 shows the ratio I_1/I_2 as a function of probe radius for two rather different sets of operating conditions. In run A the pressure change was 18 μT and the energy gain per turn 0.115 MeV. In run B the pressure change was 23 μT and the energy gain per turn 0.050 MeV. In making use of these data the values of the current ratios versus radius represented by the solid lines were used.

It is expected that, in the energy interval of interest, the gas stripping cross-section will have an approximate inverse energy dependence[1)]. It is also approximately true that the ion energy is proportional to the square of the radius of the probe. Within these approximations the equation in Fig. 6 may be used to calculate the constant k in $\sigma = k/B$. The value obtained from run B is 2.5×10^{-16} cm^{2}MeV. For run A the data were divided into two intervals. For the energy interval 14-24 MeV (radial interval 11.7 - 15.7 in.), $k = 4.1 \times 10^{-16}$ cm^2 MeV. For the energy interval 24-45 MeV (radial interval 15.7 - 19.7 in.), $k = 2.9 \times 10^{-16}$ cm^2 MeV. Our provisional result is $k = 3.2 \pm 0.9 \times 10^{-16}$ cm^2 MeV per atom of air. This value is based on a pressure change measured on an uncalibrated ionization gauge. Final results await the calibration of the gauge.

The present result is compared with other experimental values and with a theoretical calculation[1)] in Fig. 7. The cross represents a recent measurement of Pyle, Berkner, and Kaplan[2)] with 20 MeV negative deuterium ions accelerated in the Hilac at LRL. They also determined that the single-to-double stripping ratio is at least 18. This means that the present experiment essentially determines the cross-section for single stripping. The circled points are measurements of Rose, Conner,

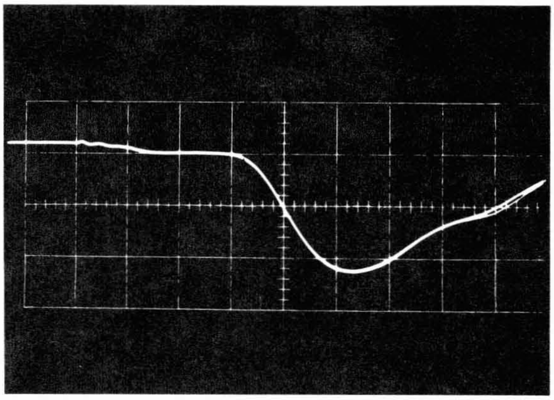

Fig. 1 A pulse of negative current to the stripper probe. The vertical scale is 1 volt/cm, the horizontal 2 μs/cm.

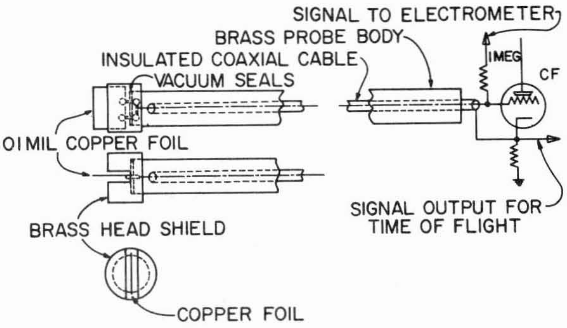

Fig. 3 The stripper probe, a simplified unit-gain cathode-follower drive circuit, and signal take-off points.

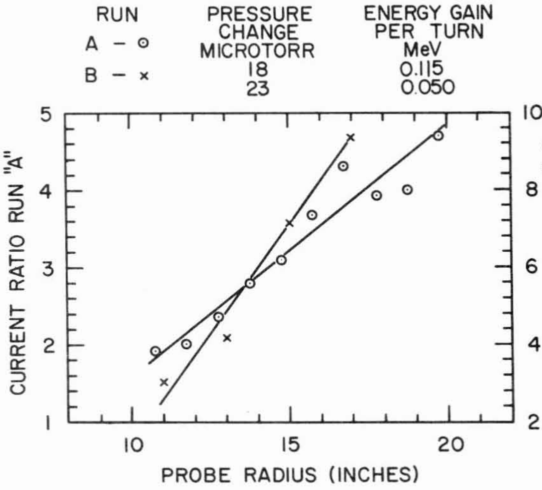

Fig. 5 Negative ion current ratio for a given change in tank pressure vs stripper probe radius.

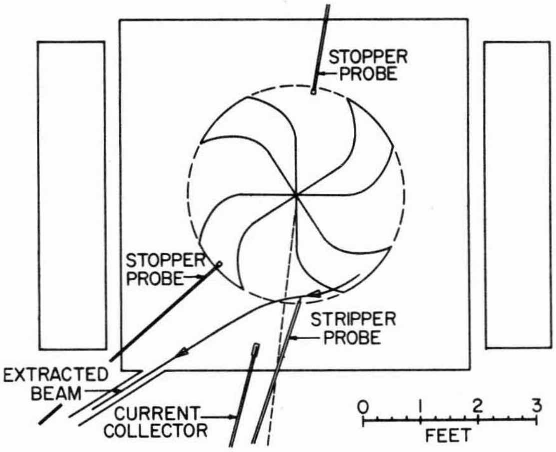

Fig. 2 Horizontal section of the cyclotron showing various probe locations. The current collector is used for electric stripping measurements. The stripper probe is shown positioned for the extraction of an external beam. For gas stripping measurements it is rotated to the dashed radial line. The stopper probes are used to check beam centering and in the electric stripping measurements.

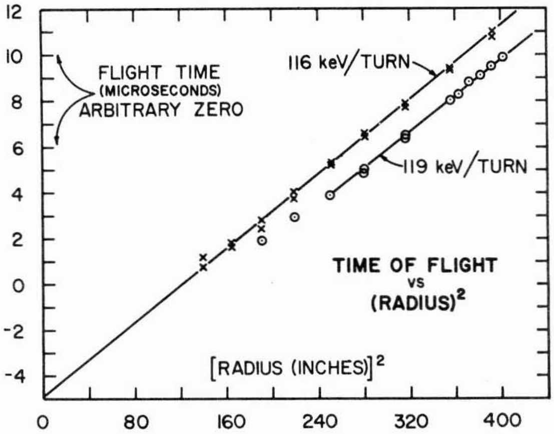

Fig. 4 Negative-ion pulse flight time as a function of radius.

σ AIR STRIPPING CROSS SECTION (CM^2 PER ATOM)

E ENERGY (MeV)

ΔE ENERGY GAIN PER TURN (MeV)

I_{11} BEAM CURRENT
RADIUS
PRESSURE

R RADIUS (CM)

N ATOMS PER CM^3

$$\sigma = \frac{k}{E}$$

$$E = KR^2$$

$$k = \frac{\Delta E}{4\pi (N_2 - N_1)(R_2 - R_1)} \ln \frac{I_{12}/I_{22}}{I_{11}/I_{21}}$$

Fig. 6 Definitions of symbols and an equation for computing the gas stripping cross-section.

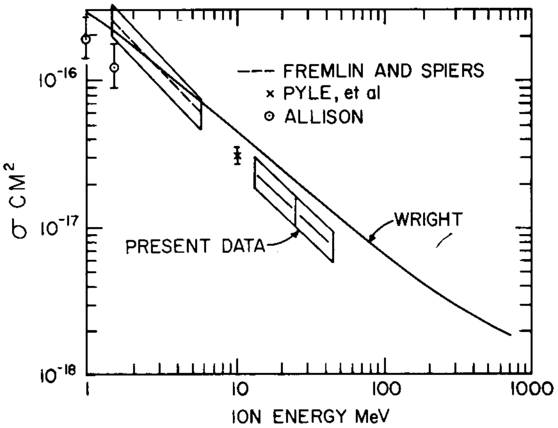

Fig. 7 Measured and theoretical values of the cross-section for a gas stripping of an electron from negative hydrogen ions by nitrogen or air "atoms".

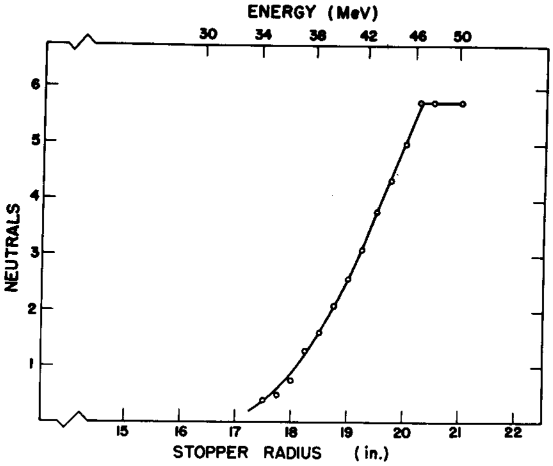

Fig. 8 Collector probe current as a function of stopper probe radius (energy).

and Bastide$^{3)}$, as reported in Allison's review article$^{4)}$. The dashed line represents a single value of k determined by Fremlin and Spiers$^{5)}$ in a cyclotron circulating-beam experiment. It is to be noted that most of the experimental values are about 2/3 the theoretical values.

Electric Dissociation Lifetime of H^- Ions

The loss of negative ions due to dissociation by the electric field $\vec{E} = \gamma(\vec{N}' \times \vec{B})$ was investigated. The velocity of the ion is v, and $\gamma = (1 - v^2/c^2)^{-\frac{1}{2}}$. For this experiment the stripper probe shown in Fig. 2 was withdrawn to the wall of the vacuum tank. The shielded current collector was used to measure the flux of neutral particles which leaves the region of circulating current. A thin foil which covers the current collector served to strip the remaining electron from the neutral particles. The current to this collector was measured as a function of the stopper-probe radius. Either one of the stopper probes shown could be used. The negative ions were circulating in the clockwise sense. The current collector received neutrals from the lower right hand hill. The stripper probe could be used to locate the region of origin of the particles, as well as to establish the fact that they were neutral.

Fig. 8 shows the measured collector current as a function of the ion energy at the stopper radius. From these data the electric dissociation lifetime τ can be determined with the following formula

$$\frac{1}{I}\;\frac{dI}{dE} = -\;\frac{2\pi\alpha}{\tau\;\gamma\;B_c(e/m)\;\Delta E}\;,$$

where α is the fraction of hill field in a sector, γB_c is the isochronous field, (e/m) is the specific charge of the ion, and ΔE is the energy gain per turn.

(1/I)(dI/dE) is the fractional decrease in circulating current per unit energy interval. These values are determined from Fig. 8 (after making corrections for beam loss by gas dissociation).

The values of τ determined from these experiments are shown in Fig. 9. They are seen to be considerably smaller than the theoretical values of Hiskes which were reported by Judd$^{6)}$, and somewhat smaller than the theoretical value of Khoe. Most of the possible sources of error lead to equal uncertainty toward larger or smaller lifetimes. Beam loss in the radial region of interest due to causes other than electric dissociation will lead systematically to an underestimate of the lifetime. The possibility that the beam has less than the expected energy at a given radius similarly leads to an overestimate of the lifetime. Much of the large uncertainty indicated in Fig. 9 arises from these two reasons.

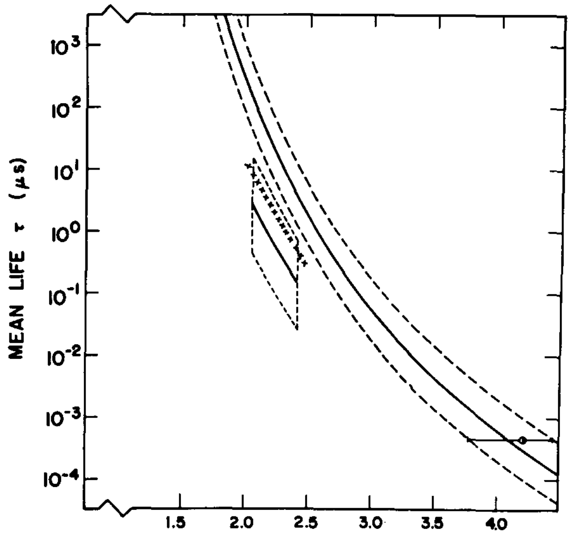

Fig. 9 Measured and theoretical electric dissociation lifetimes. The crosses are theoretical values of Khoe.

Circulating and Extracted Beams

A combination stripping and current probe was developed; the probe head is shown in Fig. 3. When the negative hydrogen ion beam passes through the stripping foil the electrons which are stripped remain in the foil. The electron current then serves as a convenient, continuous monitor of the current accelerated to the final radius of the cyclotron. Care must be exercised in the design of the stripper probe head so that low energy positive ions with highly excentric orbits are not detected. This background has a broad resonance and a magnitude on occasion ten times the negative ion current. A thin foil projecting beyond a thick shield proved most satisfactory. The shield prevents any low energy particles from stopping in the foil support structure. Under present operating conditions (base pressure, 10^{-5} T; macroscopic duty factor, 5%; Oak Ridge ion source, no puller) the stripper current is about 2×10^{-8} A, on twice the proton current. We plan to install an additional diffusion pump very soon. The expected reduction in pressure will reduce gas stripping losses by a factor of four. We also plan to increase the macrostructure duty factor from 5% to 100%. The combined changes should increase the stripper current to more than one microampere.

Beams of energy up to 47 MeV have been brought outside the vacuum tank. The energy was determined by measuring the range in aluminum. At the present time a 42 MeV beam is piped outside the main shield.

References

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7. T.K. Khoe, Private communication.

DISCUSSION

KHOE : Better integration of the WKB approximation and the use of elliptic integrals should decrease the lifetime. The actual lifetime must be lower than what I have calculated.

BLOSSER : Your error bars on the electric dissociation lifetime appear to be more than a factor of 10.

WRIGHT : They are slightly less than a factor of 10, I think.

BLOSSER : How well do you hope to do?

WRIGHT : A factor of 2 or 3 should be possible.

KERST : Can you detect an azimuthal variation in the generation of neutrals due to the increasing magnetic field at certain azimuth?

WRIGHT : We have not yet attempted to do that. Our present current collector collects from only one twelfth the given hill. If this current collector were rotated in azimuth the variation should be observed quite readily.

SCHMIDT : How can you be sure that the current you see on your collector is not due to some beam which hits the hill and scatters?

WRIGHT : The neutral ion beam would not have been cut off by the probe at the expected radius.

REISER : Did you do anything to stop protons and other molecular ions from being accelerated?

WRIGHT : No. To change from negative ions to protons we just change the magnetic field by a small amount. The ion source is re-positioned to optimize the beam.

MACQ : What, roughly, is the ratio of positive to negative ion current you get with your accelerator?

WRIGHT : At present a factor of about 1000.