Charge Distributions of Oxygen and Neon Ions Passing through Gases*

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Electrons were stripped from accelerated oxygen and neon ions by passing them through a gas. Magnetic deflection was used to select the energy and charge of the incident ions and to determine the distribution of ionic charges in the stripped beam. As the amount of gas that the ions passed through was increased, the peak of the charge distributions first shifted toward higher charge states and then became constant as equilibrium was established between capture and loss of electrons. At equilibrium in argon the charge distributions were bell-shaped, with a width of 1.8 charge states at half maximum. The average ionic charges for 3.3-, 6.1-, and 8.7-Mev O ions were 3.5, 4.8, and 5.2, respectively, and for 3.1-, 7.1-, and 10.3-Mev Ne ions 3.3, 4.9, and 6.0, respectively.

INTRODUCTION

THE state of ionization of oxygen and neon ions passing through gases with a few Mev kinetic energy has been measured. The main incentive for this work was to test the feasibility of using gas stripping as a source of highly charged "heavy" ions for injection into the heavy-ion linear accelerators that are being constructed at the University of California Radiation Laboratory and at Yale University. It was hoped that this test program would reveal the ion velocity necessary to produce the desired charge states, the number of atoms/cm^2 of gas in the stripper necessary to reach an equilibrium distribution of charge states, and whether or not some gases produce appreciably higher charges than others.

Considerable information is available on the capture and loss of electrons by protons and helium ions passing through matter.[1] Lassen[2] has measured the average charge of fission fragments passing through solids and gases, and theories for the capture and loss of electrons by fission fragments have been worked out by Bohr,[3] Bell,[4] and Bohr and Lindhard.[5] Measurements of the state of ionization of accelerated nitrogen ions emerging from thin foils have been published during 1954 by Reynolds, Scott, and Zucker,[6] Reynolds and Zucker,[7] and Stephens and Walker.[8] Very little information is available, however, on the stripping in gases of ions in the mass region near oxygen and neon.

EXPERIMENTAL PROCEDURE

The 4-megavolt Van de Graaff, which is normally used to inject protons into the UCRL 40-foot linear accelerator, was used to accelerate oxygen and neon ions for this experiment. The ions were made in the regular proton source by supplying oxygen or neon instead of hydrogen. Figure 1 is a plan view of the accelerators and the auxiliary equipment used. The ions formed in the ion source were accelerated in the Van de Graaff column, coasted through the linear accelerator (with the rf turned off), passed through the gas stripper, were deflected through 12.6° by the analyzing magnet, and finally were detected in a stationary Faraday cup. The stripper, shown in Fig. 2, was similar to one used by Bittner[9] to strip He ions. It consisted of a stainless steel tube $\frac{1}{8}$ inch in inside diameter and 20 inches long. The tube was suspended in a vacuum chamber on Wilson seal rods with offset connections so that it could be aligned with the beam. Gas could be admitted from a flexible tygon hose connected at the center of the tube. A diffusion pump connected to the vacuum jacket maintained a pressure of a few hundredths μ Hg at the ends of the tube. A McLeod gauge was used to measure the pressure at the center of the tube and ion gauges read the pressure in

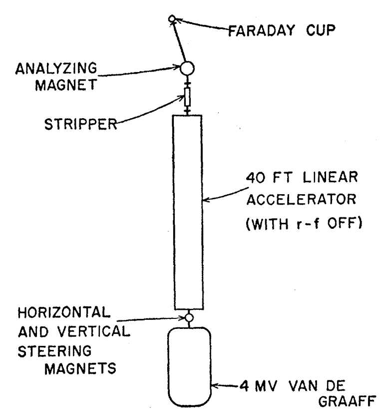

FIG. 1. Layout of accelerators and experimental apparatus.

* This work was done under the auspices of the U. S. Atomic Energy Commission.
[1] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. **25**, 779 (1953).
[2] N. O. Lassen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **23**, No. 2 (1945); Phys. Rev. **68**, 142 (1945); Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **25**, No. 11 (1949); Phys. Rev. **79**, 1016 (1950); Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **26**, No. 5 (1951); Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **26**, No. 12 (1951).
[3] N. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **18**, No. 8 (1948).
[4] G. I. Bell, Phys. Rev. **90**, 548 (1953).
[5] N. Bohr and J. Lindhard, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **28**, No. 7 (1954).
[6] Reynolds, Scott, and Zucker, Phys. Rev. **95**, 671 (1954).
[7] H. L. Reynolds and A. Zucker, Phys. Rev. **95**, 1353 (1954).
[8] K. G. Stephens and D. Walker, Phil. Mag. **45**, 543 (1954).
[9] J. W. Bittner, Rev. Sci. Instr. **25**, 1058 (1954).

the vacuum jacket of the stripper and in the linear accelerator tank.

When oxygen or neon was used in the ion source it was found that not only singly ionized ions came out of the Van de Graaff, but doubly and triply ionized ions as well. Ions that emerged from the accelerating column with a particular charge had a continuum of energies extending down from the energy which an ion of that charge would gain by falling through 4 megavolts. The origin of the energies that are not integral multiples of 4 Mev is thought to be change of charge of the ions due to collisions with gas atoms in the column. The column of this Van de Graaff is pumped from the exit end only and is estimated to contain 70 μ-cm of gas, which is sufficient to produce the distribution of charge states observed. The steering magnets between the Van de Graaff and the linear accelerator can be adjusted so that only ions of a single charge state and a narrow range of energies enter the stripper.

The procedure in making runs was as follows: the leak rate into the center of the tube was set to provide the desired pressure; then the current received by the Faraday cup was plotted as a function of the analyzing-magnet current while the beam energy and current were held constant. The magnet current was swept slowly and continuously by hand, and the output voltage of the electrometer connected to the Faraday cup was plotted *vs* magnet current on a Speedomax x-y recorder. Figure 3 gives an example of the spectra due to 6.9-Mev Ne^{+2} ions with various pressures in the stripper. The peaks represent ion currents of about 10^{-11} amp. The charges corresponding to the peaks in a monochromatic spectrum could be identified because the fields were inversely proportional to the charges. After identification of the e/m of a peak, its energy was determined from the magnet current, the magnetization curve of the magnet, and a calibration point obtained by observing the current required to deflect 31.5-Mev protons through the same angle.

In agreement with theory, no significant loss in kinetic energy by the ions due to passing through the gas was observed (i.e., the loss was less than 1 percent).

To obtain the distribution in charge states for a spectrum, the peak amplitude of the current in each charge state was divided by its charge number to obtain the relative number of ions per second, or the "ion current." Each ion current was then divided by the sum of the ion currents to give the fraction of the ions in that charge state.

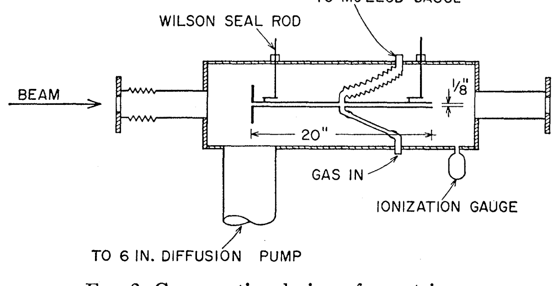

FIG. 2. Cross-sectional view of gas stripper.

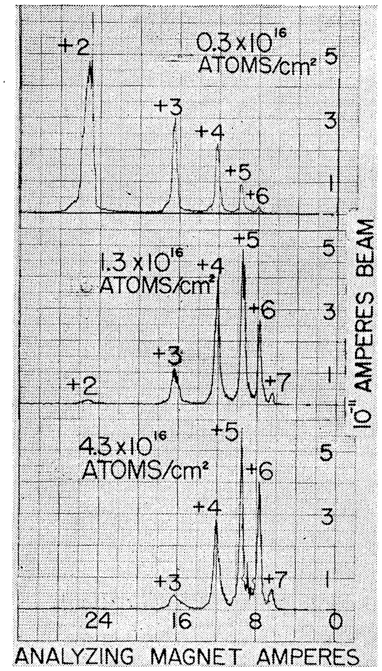

FIG. 3. Samples of spectra for 6.9-Mev Ne^{+2} ions stripped in argon for pressures of 1μ, 13μ, and 47μ at the center of the stripper tube. The numbers of atoms/cm^2 for these pressures are 0.3×10^{16}, 1.3×10^{16}, and 4.3×10^{16}, respectively.

To correct for fluctuations in the incident-beam current during the plotting of a spectrum, three spectra were taken under each set of conditions, and the fractional ion currents quoted are the averages of the three values. In some cases the ions under investigation could not be separated completely from the other components of the Van de Graaff beam with the steering magnets. In these cases the maximum possible systematic error in subtracting unwanted components from a spectrum has been added to the rms deviations from the average of the three runs to obtain the experimental uncertainties quoted. It was assumed that the relative heights of the peaks were not affected by multiple scattering in the gas. This is in agreement with theory and with the observed line widths, since theory indicates that multiple scattering in the gas is nearly independent of ionic charge and no dependence upon ionic charge was observed.

The readings of the pressure gauges were used to calculate the number of atoms/cm^2 of gas that the beam passed through before entering the analyzing magnet. For the lower pressures used the flow in the tube was molecular, and the pressure fell linearly from its value at the center to that at the ends of the tube. For higher pressures in the transition region between

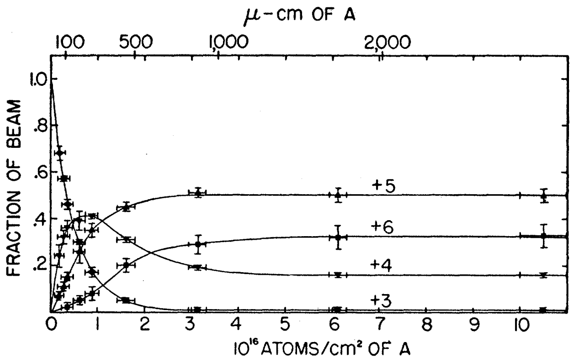

FIG. 4. Fraction of 8.7-Mev oxygen ions in each charge state *vs* the amount of argon gas they have passed through. The scale at the top gives the amount of argon gas in units of (μ Hg)-cm.

molecular and viscous flow, Knudsen's empirical equation was used to correct the molecular-flow calculation. This correction increased the calculated number of atoms/cm² in the tube by 1 percent when the pressure at the center of the tube was 40 μ Hg and by 4 percent when the pressure at the center was 80 μ Hg. The residual gas in the linear accelerator and the mercury vapor in the stripper tube from the untrapped McLeod gauge caused some stripping even when no gas was admitted to the tube. The errors indicated in the number of atoms/cm² include the uncertainty from the mercury vapor pressure and the linear accelerator pressure as well as the uncertainty in the McLeod gauge readings.

RESULTS

Figure 4 shows the distribution in charge states of 8.7-Mev oxygen ions *vs* the number of atoms/cm² of argon gas that the beam has penetrated. These ions entered the gas as O^{+3} ions. As the gas pressure was increased the distribution at first shifted toward higher charges and eventually approached an equilibrium distribution that did not change with further increase in pressure. 40 μ Hg pressure at the center of the 50 cm tube, or about 10^3 μ-cm, or about 3.5×10^{16} atoms/cm², brings each of the charge states to within 1 percent of its final equilibrium current. There is no evidence for charge exchange due to collisions with the metal tube wall, but we cannot rule out the possibility that as many as 10 percent of the original O^{+3} ions were changed to higher states by this process.

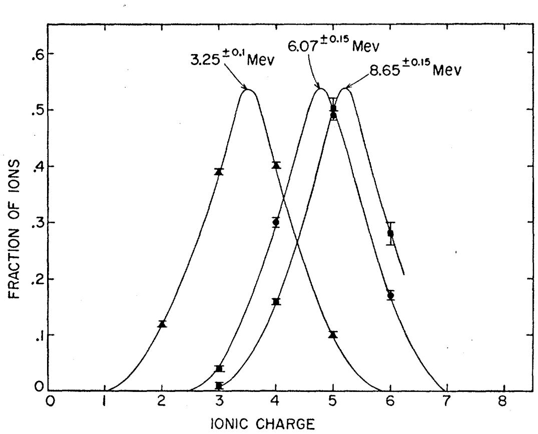

FIG. 5. The ordinate is the fraction of 3.3-, 6.1-, and 8.7-Mev oxygen ions in each charge state after passing through enough argon to produce equilibrium distributions. The abscissa is the charge of the ions in units of the charge of an electron.

The equilibrium distributions in argon were found for oxygen ions of three different energies and for neon ions of three different energies. These data are summarized in Figs. 5 and 6, respectively, where the fraction of ions in each charge state is plotted *vs* the charge. In this energy range smooth curves drawn through the points indicate a roughly symmetrical bell-shaped distribution. Changing the energy shifts the whole curve without appreciably changing its shape or width. The 8.7-Mev oxygen distribution illustrates an exception to this rule. If this distribution were symmetrical there would be about 5 percent O^{+7} ions; actually none were observed. This is not surprising in view of the relatively large binding energies of the K-electrons.

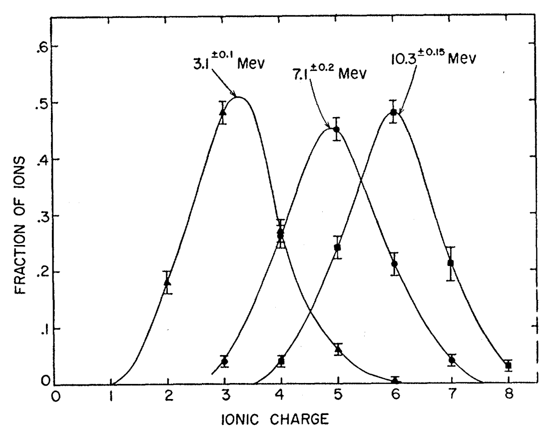

FIG. 6. Fraction of 3.1-, 7.1-, and 10.3-Mev neon ions in each charge state after passing through enough argon to produce equilibrium distributions.

Several different stripping gases were tried to see if some produced higher charges than others. H_2, He, N_2, and A gases were compared, using 7.1-Mev neon ions, and no significant difference was found between the equilibrium distributions. N_2, Kr, and Xe gases were compared, using a 7.2-Mev oxygen beam, and again the equilibrium distributions did not differ significantly. However, the number of atoms/cm² of stripper gas required to produce an equilibrium distribution decreased as its Z increased. Lassen has found that the steady-state average charge of fission fragments in He is about 10 percent less than that in H_2 gas.[2] The experiment reported here does not rule out the possibility of an effect of this magnitude.

Lassen also observes an increase of the average charge with increasing gas pressure, which he attributes to a contribution to electron loss of excited states with lifetimes comparable to the time between excitations. He finds an increase in average charge of about 7 percent per 10 mm increase in gas pressure. In our experiment the highest pressures used were about 0.1 mm, so that this effect was not detectable.

Gluckstern has calculated electron capture and loss cross sections using a modification of Bell's theory.[4] In the following paper[10] he compares his theoretical results with cross sections deduced from Fig. 4 and with the equilibrium distributions in charge states given in Figs. 5 and 6.

We wish to acknowledge valuable contributions to this experiment by many members of the linear accelerator operating crew and of the groups from Yale University and from the Radiation Laboratory that are designing the heavy-ion accelerators.

[10] R. L. Gluckstern, following paper [Phys. Rev. 98, 1817 (1955)].

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Electron Capture and Loss by Ions in Gases*

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Capture and loss cross sections for ions of intermediate atomic number ($Z_1=8$ to 18) passing through low-pressure gases have been calculated. A modified form of Bell's model was used, leading to lower capture cross sections than the original model. The resulting equilibrium charge distributions obtained compare favorably with the experimental results of Hubbard and Lauer. The individual cross sections were obtained from the observed dependence of the charge distribution on the stripper thickness; these results agree reasonably well with the predictions of the calculations. Capture and loss of two electrons in a single collision may be significant, but the effect on the charge distributions should not be too great.

I. INTRODUCTION

THE heavy-ion linear accelerators at the University of California Radiation Laboratory and at Yale University are being designed to include gas strippers to increase the efficiency of the ion acceleration. Experiments described in the preceding paper have been performed by Hubbard and Lauer[1] to determine the charge distributions for stripping oxygen and neon ions in various gases, using the University of California Radiation Laboratory 4-Mv Van de Graaff injector to the 40-foot proton accelerator. The purpose of this paper is to compare their results with predictions based primarily on the model that Bell[2] used for investigation of the charge distribution of fission fragments in gases.

The most recent theoretical investigations of electron capture and loss have been undertaken by Bohr,[3] Bell,[2] and Bohr and Lindhard.[4] Bohr[3] and Bohr and Lindhard[4] use a simplified Fermi-Thomas model for the electron shielding, and base their estimate of capture and loss cross sections on general features of a classical description of the ion-atom collision. Bell[2] uses a more detailed Fermi-Thomas model for the position, velocity, and "binding force" of the electrons involved in the collision. According to Bohr and Lindhard,[4] the agreement between the predictions of the two methods for fission fragments is good, considering the complicated nature of the actual collision. In this paper a slight modification of Bell's method is used to calculate the loss and capture cross sections and the charge distributions for stripping of oxygen through argon ions in a variety of stripping gases for a velocity range $3v_0$ to $7v_0$ ($v_0=c/137$).

II. CALCULATION OF CROSS SECTIONS AND EQUILIBRIUM CHARGE DISTRIBUTIONS

The stripping pressures used by Hubbard and Lauer[1] are sufficiently small that the time between successive loss or capture collisions is much greater than the average lifetime of excited electron states induced in the ion in these collisions.[5] For this reason the ion can be considered in its ground state before each collision, and Bell's model of a "rarefied" gas stripper applies.

For the capture cross section, Bell's model is applied with the stripper electrons assumed to be located at the "half-charge" radii determined from a Fermi-Thomas model, i.e., the total charge inside the sphere corresponding to the nth electron is $Z_2-n+\frac{1}{2}$. The capture cross section for each stripper electron by a point charge representing the ion is calculated by kinematic considerations regarding the liberation and

* This work was performed at the Radiation Laboratory, University of California, and was supported by the U. S. Atomic Energy Commission Contract AT (30-1) 1691.

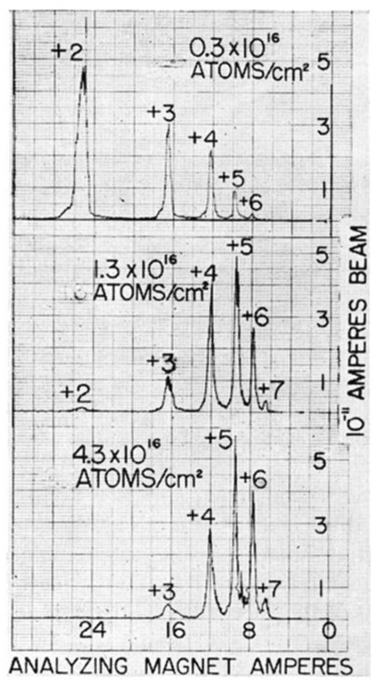
[1] E. L. Hubbard and E. J. Lauer, preceding paper [Phys. Rev. 98, 1814 (1955)].

[2] G. I. Bell, Phys. Rev. 90, 548 (1953).

[3] N. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 18, No. 8 (1948).

[4] N. Bohr and J. Lindhard, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 28, No. 7 (1954).

[5] As estimated by Bohr and Lindhard [reference 4, Eq. (6.4)].



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