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A Heavy-Ion Energy Loss Spectrometer*

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A high resolution system for the measurement of the energy loss spectra of 20–250 keV heavy ions incident on gas targets is described. The high resolution is obtained by decelerating the ion beam to a low, well defined energy before performing the energy analysis. The energy loss spectrum is determined by changing the accelerator energy to compensate for energy lost in collisions with the gas atoms. The system is arranged so that normal fluctuations in the accelerator's power supply do not affect the energy resolution. The resolving power of the system is 2.5×10^4. The primary proton beam has a detected WHM of 2 V at 50 kV. An energy loss spectrum is shown for which the collision-excited 1^1S–2^1P transition in helium is clearly resolved.

INTRODUCTION

THE study of energy loss processes for heavy ions with kinetic energies in the range 20–250 keV incident on gas atoms can be performed in two manners. One method is to study the secondary particles or the photons leaving the collision region. The other is to study the primary particle as it leaves the collision region. The former method often does not define the reaction, or reactions, taking place. The latter method has, until now, lacked sufficient resolution for the measurement of the desired cross sections. The apparatus described in this article provides the resolution required for the calculation of cross sections from a study of the energy loss spectra of the primary ion beam.

The conventional system used to study energy loss spectra, or to measure stopping power,[1] consists schematically of an accelerator producing heavy ions, a collision region, and an analyzer. The incident ion-beam distribution from the accelerator is measured without any gas in the collision region and measured again with a known amount of stopping gas. The resolution in the energy loss spectra obtained in this way is a function of several factors. Among these are the energy spread of the ion beam as it is formed in the ion source, the resolution of the analyzer system, and the ripple and fluctuations in the high voltage power supply system. The energy spread due to the ion source and extraction system is a strong function of the design of the ion source system, but high current sources have been obtained with ion energy half-widths of less than 1 eV. In theory, it should be possible to build an analyzer with as much resolution as desired; however, the inherent in-transit loss of beam current and the requirements of size and cost place practical limitations on the design of the analyzer. While a resolution of one part in 10^3 is not too difficult to obtain, a resolution of greater than one part in 10^4 is quite difficult and expensive to acquire. Even if an analyzer could be built with sufficient resolution, typical regulated 250 kV high voltage power supplies are usually regulated to no better than 0.03% and have 0.02% ripple. This places a practical limit on the energy spread of about 0.04% of the incident-beam energy even with the most sophisticated analyzers. The techniques employed in this experiment to improve the resolution involve the use of an acceleration–deceleration arrangement to obtain the high resolution required for energy loss spectra measurements.

These techniques which are used here with heavy ions are similar to those employed by Boersch *et al.*[2,3] with electrons and to those of Barat *et al.*[4,5] They differ from these experiments with respect to the energy range and particle

* This work was supported by a grant from the National Science Foundation. The work was initiated under a grant from the Research Corporation.

[1] J. T. Park and E. J. Zimmerman, Phys. Rev. **138**, A1317 (1965).

[2] H. Boersch, J. Geiger, and W. Steckel, Z. Physik **180**, 415 (1964).

[3] H. Boersch, J. Geiger, and H. J. Reich, Z. Physik **161**, 296 (1961).

[4] M. Barat, J. Boudon, and Albert Septier, Compt. Rend. **259**, 129 (1964).

[5] M. Barat, J. Boudon, and A. Septier, J. Microscop. 2, 381 (1963).

in the case of Boersch *et al.*, and with respect to the method and experimental arrangement in the case of Barat.

The 250 kV accelerator at the University of Missouri-Rolla produces a beam of ions which passes through a stopping cell. After passing through the stopping cell the exit beam is decelerated to about 2 keV before entering an electrostatic analyzer. By performing the analysis at reduced beam energy the over-all resolution is greatly increased. The increased resolution of the acceleration–deceleration technique permits an accurate determination of the exit beam distribution. This makes precise measurements of energy loss cross sections possible. The increased resolution permits a study of the energy loss spectrum which can provide information on the relative probabilities of the various energy loss processes and on the cross sections for some specific energy loss processes.

APPARATUS

Accelerator

The 250 kV ion accelerator system at the University of Missouri-Rolla is specifically designed for the measurement of energy loss spectra. Its accelerating column is of the conventional constant voltage gradient design. The accelerating column forms a thick electrostatic lens of the type studied by Elkind.[6] Wherever practical limitations permitted, the design parameters were chosen so as to form as weak an electrostatic lens as possible. The accelerating column is built of 13 identical sections consisting of stainless steel electrodes glued to glass insulators with an epoxy adhesive. The column is stressed with nylon ropes to prevent cracking and distortion in the column during evacuation. The stainless steel electrodes are of a concave nesting design to reduce forces on the beam due to asymmetric charge creepage on the glass insulators or by charges deposited on the insulators resulting from scattered ions or electrons. The last electrode is part of a system of electrodes arranged to repel secondary electrons.

The voltage gradient between the electrodes in the accelerating column is obtained by a string of 60 MΩ (DC-5 0.5%) resistors in silicon potting compound enclosed in a Plexiglas box. The box rests on the accelerating column, and the resistors make contact with the electrodes through springs in the bottom of the box. This method has proven to be simple and relatively foolproof. The current through these resistors is monitored from the control console.

The measurement of the accelerator voltage is made by a differential voltmeter. A voltage divider is connected across the accelerator output and mounted between corona shields in an oil filled glass cylinder. The differential voltmeter is connected across the last resistor (600 kΩ) and reads directly in kilovolts. Calibration has shown the voltage measurement to be accurate within the specifications of the 0.5% 10 MΩ DC-5 resistors used in the divider.

The accelerator cage is an aluminum box 76×91×101 cm in size. The corners have a radius of curvature of 18 cm. The openings are recessed and covered by clear Plexiglas doors with screen wire electrostatic shielding. The meters which monitor the focusing voltage, extraction voltage, ion source gas pressure, etc. are visible through these Plexiglas doors. The accelerator cage is supported on 30 cm diam glass tubes containing the control rods, the differential pumping pipe, and the voltage divider.

Several ion sources have been tried with the accelerator. The Colutron ion source[7] has proven to be the most satisfactory source of monoenergetic ions. This source is designed to produce ion beams from solids, liquids, or gases. The Colutron source has an energy spread of about 0.11 eV.[8] The measurements on this source by Wåhlin, however, were made under different conditions than existed in our case.

The source is cooled by circulating transformer oil through its case. The oil passes through plastic tubing to a heat exchanger located outside the protective enclosure.

The ion source is differentially pumped by a 700 liter/sec diffusion pump. The pump is located in the accelerator base and is connected to the extractor assembly by a 15 cm diam glass pipe. The purpose of this pump is to remove most of the gas which would otherwise enter the accelerator and increase the scattering of the ion beam.

Focusing of the ion beam is accomplished by using the focal properties of the column and an einzel lens. The ion beam is extracted from the ion source by an extractor electrode. The ion beam then passes through the einzel lens into the accelerator column. The lens system is designed so that it is relatively insensitive to the total acceleration voltage. The column forms a relatively weak, thick lens so that most of the focusing of the beam is accomplished by the extractor electrode and the einzel lens. These properties of the focusing system permit changing the high voltage by several kilovolts without any effect on the observed beam current.

The focus and extractor voltages as well as the ion source parameters are adjusted by means of Variacs in the high voltage terminal. The Variacs are connected by nylon rods to selsyns, which are controlled from the main control console.

The control console consists of two sections. The main stationary section contains the selsyns controlling the focus and extractor voltages, the ion source filament current, and the ion source pressure in the accelerator. It also contains the column current meters and the Keithley

[6] M. M. Elkind, Rev. Sci. Instrum. **24**, 129 (1953).

[7] Colutron Corporation, Box 1288, Boulder, Colorado.

[8] L. Wåhlin, E. E. Dept., University of Colorado (private communication).

660 differential voltmeter which measures the accelerator voltage. The stationary section of the control console is connected to the high voltage control and to the vacuum gauge controls. The other section of the control console is mobile and can be moved about the laboratory to the position most convenient for the operator. This mobile control unit contains the controls for the parameters which are most likely to need adjustment during a given experimental measurement, namely, the controls for the alignment and deflection plates, an additional focus control, and the switching magnet control.

The ac power required in the accelerator and decelerator cages is supplied by a 10 kVA isolation transformer. This transformer supplies four 110 V ac lines, with breakdown voltage of 50 kV between lines and 250 kV to ground. Each line can supply 25 A at 110 V ac. The ac power into this isolation transformer is regulated.

The accelerator drift tube is made from a 15 cm diam glass cross. The drift tube is separated from the accelerator by a 15 cm gate valve and a bellows to permit vacuum isolation of the acceleration column. The base of the glass cross forming the drift tube is connected to a liquid Freon-trapped 1800 liter/sec diffusion pump. There are four pairs of electrostatic deflection plates in the horizontal arms of the cross. These are arranged so that the beam can be translated in any desired direction or deviated through a small angle. This additional flexibility eases the mechanical alignment requirements.

Decelerator

The decelerating column is essentially identical to the accelerating column. It has a constant voltage gradient maintained by a resistor string similar in construction to the one on the accelerator column. A constant voltage gradient in the decelerator seems to be satisfactory for most of the tests made to date.

The decelerator cage is similar in design to the accelerator cage except that it is considerably longer in order to have room for the electrostatic analyzer, several power supplies, and the data acquisition system. It is a box 76×91×183 cm in size with corners having a 18 cm radius of curvature. It is supported on 30 cm diam glass tubes and 36 cm diam fiberglass tubes.

The decelerator section is evacuated by a Freon-trapped 1500 liter/sec diffusion pump. The decelerator column and its pump may be isolated from the rest of the system by a 15 cm gate valve. The diffusion pump and traps are mounted on the base of a T which is mounted through a bellows onto the decelerator column. Two pairs of deflection plates are included in this T. This permits some additional alignment of the exit beam from the stopping cell.

Offset Power Supplies

The offset voltage (V_o) is obtained from a precision 0 to 10 kV high voltage supply having a 0.001% regulation and 10 mV resolution. The supply has less than 0.005% voltage drift per hour. The dial readings are accurately calibrated, permitting differences in offset voltage to be measured to 0.5%. Nylon rods are connected to the control dials on the offset supply so that it can be varied during operation. A small voltage ΔV is added to this offset voltage and can have any value between ±180 V. It is determined by a variable regulated power supply which is controlled from outside the protective enclosure through a nylon rod. This nylon rod may be rotated either manually or by a variable speed motor. The ΔV voltage may be varied uniformly at rates from 0.04 to 40 V/min.

Electrostatic Analyzer

The ion beam passes through the decelerator column and is analyzed by an electrostatic analyzer. This analyzer is of the 127° focusing design.[9,10] The analyzer plates are constructed of 2.54 cm thick curved bars of 304 stainless steel, which were machined and polished to provide a mean radius of 25.4 cm with a plate separation of 1.295 cm. The 7.6 cm wide plates are supported by high density alumina standoffs. A retractable Faraday cup is provided at the entrance to the analyzer to measure the total current entering the analyzer. The entrance slit confines the beam to the central portion of the analyzer plates so that edge effects do not disturb the ion trajectories. The entrance and exit slits are biased so that the ion beam enters the analyzer at the equilibrium trajectory potential. The analyzer slits have been designed so that they are located in the focal plane of the analyzer. The calculated resolving power is 1000 which agrees very well with the observed resolution determined from studies of the measured energy distribution.

The analyzed beam is detected by a 14-stage electron multiplier which is located just beyond the exit slits of the analyzer. The voltage for the electron multiplier is provided by a 3 kV regulated power supply. The signal from the electron multiplier is fed into the data acquisition system described below. The deflection voltage for the analyzer is supplied by a 0–6 kV regulated power supply. This supply has 0.001% regulation. It has less than 0.005% voltage drift per hour, and its dial readings are accurately calibrated to 0.25%. Its resetability is 0.05%. Nylon rods are connected to the control dials on this supply so that it can be varied while the decelerator cage is at high voltage.

Data Acquisition System

A data acquisition system has been built to make measurements within the decelerator cage while it is at

[9] A. L. Hughes and V. Rojansky, Phys. Rev. **34**, 284 (1929).
[10] R. Herzog, Z. Physik **89**, 447 (1934).

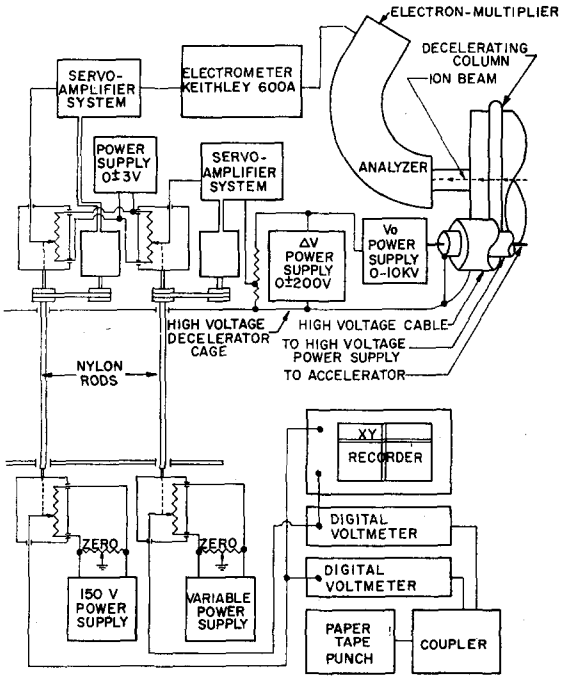

FIG. 1. Schematic drawing of the data acquisition system.

high voltage (see Fig. 1). The current from the electron multiplier is fed into an electrometer whose output drives a null-balancing servosystem. The servomotor controls a nylon rod which is connected to the balancing potentiometer in the high voltage terminal and a readout potentiometer at ground potential. Careful studies using one digital voltmeter to read the electrometer output and another to measure the output voltage from the readout potentiometer have shown the readings to be proportional to better than 0.1%. A similar servosystem is used to provide a voltage from a readout potentiometer at ground potential which is equal to $\Delta V/10$ to better than 0.1%.

The voltages from the readout potentiometers, which are proportional to ΔV and the ion current I, are fed to a X–Y recorder and are plotted out directly. The X and Y voltages are simultaneously fed into digital voltmeters having 1-2-4-8 BCD parallel outputs. A parallel–series converter has been built and the readings are punched on a paper tape for later analysis by a computer.

Stopping Cell

The stopping cell consists of a differentially pumped chamber shown in Fig. 2. The stopping cell is 6.345 cm long and its ends are sealed with stainless steel disks containing 0.051 cm apertures. It is connected by 1.2 cm i.d. tubing to the differential pressure meter and the McLeod gauge. The stopping cell is located between two differential pumping regions. Gas entering these differential pumping sections from the stopping cell apertures is evacuated by a 1200 liter/sec diffusion pump. Ion gauges measure the pressure in both the differential pumping sections so that corrections can be made for the gas in these regions. Tubes containing 0.127 cm apertures extend into both the differential pumping sections to 0.998 cm from the ends of the stopping cell. Gas leaking through the apertures at the ends of these tubes is evacuated by either the diffusion pump on the decelerator or the accelerator diffusion pump. The apertures in the tubes and those in the stopping cell are carefully aligned to maximize beam transmission. The temperature of the stopping gas cell is measured by a thermometer recessed into the body of the cell. Retractable, biased Faraday cups are located at the entrance and exit of the stopping cell unit.

The pressure of the gas is measured with a MKS Baratron[11] 77M-XRP differential pressure meter with 77+1−1 head. This unit has a ±1 Torr range. It uses a taut metal membrane with capacitive sensing to determine the pressure. Its accuracy is 0.02% of full range plus 0.05% of dial reading with reference to a calibration chart. A stainless steel valve manifold assembly permits the pressure meter to be valved out of the system. It also provides additional accuracy by valving the two ports together to accurately zero the meter before the measurement is started. In this case the accuracy is increased to 0.005% full range plus 0.05% of the dial reading.

The meters can be calibrated with a McLeod gauge. The heights of the mercury columns in the gauge are determined by a cathetometer which will permit reading the

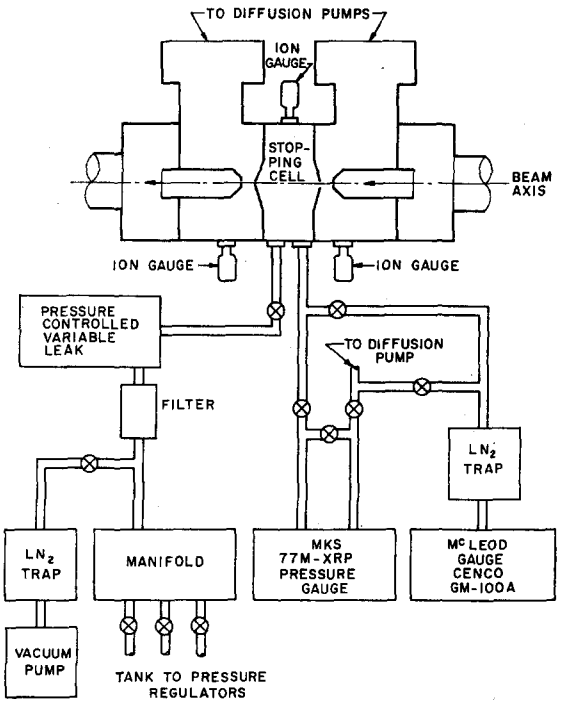

FIG. 2. Diagram of the stopping cell and gas handling equipment.

[11] M.K.S. Instruments, Inc., Burlington, Mass.

heights of the mercury columns to 0.05 mm. The pressure meters and the McLeod gauge are connected to the stopping gas cell by 1.2 cm diam stainless steel bellows.

The stopping gas is introduced into the stopping cell through a variable leak which is adjusted by a pressure controller. The pressure controller uses feedback from the differential pressure meter to maintain the stopping cell pressure at the desired value. The gas pressure from the tanks is first reduced by a pressure regulator.

Switching Magnet

A switching magnet is located between the decelerator and the vacuum chamber containing the stopping cell. The magnet is designed to provide a mass energy product of 125 at 30°, which will permit its use with the heaviest ions being considered. The switching magnet system has ports at 0, ±15, ±30, and ±45°. Its power supply has long term stability of 1×10^{-5} of its maximum current. This magnet makes the accelerator available for other experiments and provides a mass separation of the beam.

High Voltage Power Supply

The high voltage for the accelerator is supplied by a 250 kV regulated power supply. This supply has an output voltage range of 10 to 250 kV with output currents up to 2 mA. The load regulation is 0.03%, and the line regulation is 0.02% with less than 0.02% rms ripple. The supply is fully metered and provided with continuously variable output control with minimum increments of 0.03% of the voltage rating.

The laboratory is air conditioned and will soon have an additional electrostatic filtering system installed to keep down contamination due to dust. The accelerator and decelerator are located in wire mesh enclosures whose doors are directly interlocked with the high voltage supply and with automatic shorting bars.

METHOD

The experimental methods used to measure the energy loss cross sections or to obtain the energy loss spectra are basically the same. The major difference is the range of pressures used in the stopping cell. Figure 3 provides a schematic drawing of the entire apparatus.

The beam extracted from the ion source passes through an einzel lens into the main accelerating column. The ion source is connected to the positive terminal of a precision power supply (0–10 kV) which provides a positive offset voltage V_o. The negative terminal of this supply is connected to a variable power supply which supplies an additional smaller voltage ΔV. The high voltage power supply providing a voltage V is connected to the common of the ΔV power supply and to the decelerator cage. The ions are, therefore, accelerated through a total voltage of

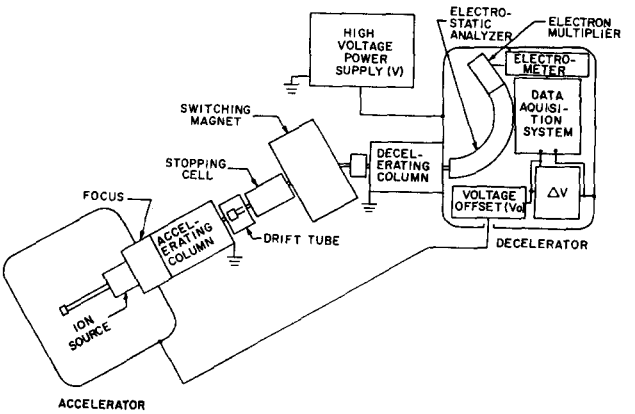

FIG. 3. Schematic drawing of the acceleration–deceleration system.

$V+V_o+\Delta V$. They then enter a drift tube where electrostatic deflection plates align the beam with respect to the apertures of the stopping gas cell which follows. After passing through the stopping cell, the beam is magnetically analyzed to remove the undesired ions and is then decelerated through voltage V. The beam now enters the electrostatic analyzer which is located in the decelerator cage. The analyzer detects ions having the correct energy for the setting of its electrostatic field.

With no gas in the stopping cell, the voltage ΔV is set to zero and the ion beam is focused on the slits of the electrostatic analyzer. The electrostatic analyzer voltage is then set to maximize the detected ion beam current. The analyzer is set to detect an ion reaching it with an energy qV_o+E_p, where E_p is the most probable kinetic energy of an ion in the ion source. The electrostatic analyzer voltage, the voltage on the einzel lens, the offset voltage V_o, the high voltage V, the deflecting magnet current, and the electrostatic deflection voltages are not adjusted again during an experimental measurement. With all other parameters held fixed, the detected current is measured as a function of ΔV. Since the analyzer has a finite resolving power, ions with energies slightly different from the desired energy will have a probability of being detected. The apparatus resolution function represents the dispersion effects of the entire apparatus on the ion source energy distribution, including the analyzer resolution. The zero energy-loss distribution obtained in this measurement is therefore a convolution of the true ion source energy distribution and the apparatus function.

When gas is present in the stopping cell, the ion beam loses energy due to the resulting collisions. An ion formed in the ion source with the most probable energy E_p, but which has lost an energy ΔE due to collisions, is now detected by the analyzer electron multiplier if $\Delta E=q\Delta V$, i.e., if it arrives at the analyzer with kinetic energy equal to qV_o+E_p. To be detected, such an ion must enter the decelerating column with the energy $E_p+q(V+V_o)$ and

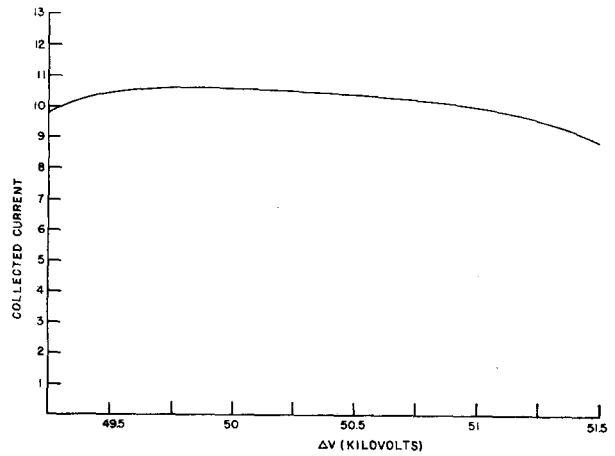

FIG. 4. Transmitted ion current as a function of the accelerator voltage.

reach the analyzer with the energy E_p+qV_0 since $E_p+q(V+V_0+\Delta V)-\Delta E-qV=E_p+qV_0$ when $\Delta E=q\Delta V$. By varying ΔV, the energy loss spectrum can be obtained. The actual current detected as a function of ΔV is a convolution of the spectrum indicated above with the ion source energy distribution and the apparatus function.

This method eliminates the difficulties of determining the effect of changing deceleration conditions. It assures that all of the ions being detected pass through the magnet and enter the decelerating column and the analyzer with the same energy regardless of the energy lost by the ions in the stopping cell. The only change is an increase in the acceleration voltage by ΔV.

The high voltage V is connected first to the decelerator and then through the ΔV and V_0 power supplies to the accelerator. Any fluctuations in the high voltage power supply will be added to both acceleration and deceleration voltages. Small high frequency fluctuations in the high voltage are efficiently filtered by the high voltage power supply and large catastropic events are infrequent and easily detected. Fluctuations with risetimes which are long compared to the time of flight of the ions in the system will cancel out of the equation giving the energy loss spectrum. These fluctuations will only contribute to the dependence of the energy loss spectrum on total energy. Since this energy loss spectrum is a slowly varying function of total energy and the fluctuations are small, the effects of fluctuations in the high voltage supply on the energy loss spectrum are too small to be detected.

RESULTS

Figure 4 shows the detected ion current passing through the empty stopping cell as a function of the total voltage. The beam was focused on the analyzer slits with a total accelerating voltage of 50 kV. This voltage is then changed without refocusing the beam. The curve representing the detected current shows that the accelerating voltage can be changed by 1 kV without significantly affecting the transmitted current. The data shown in Fig. 4 were taken under conditions where the beam required electrostatic alignment for maximum beam transmission through the stopping cell. The small decrease in detected intensity with changing voltage is primarily due to the need to change the deflection plate voltages as the total beam energy is changed. This problem can be greatly reduced by improving the mechanical alignment so that less electrostatic alignment is required. Such modifications to the system are being made. The fact that the spatial density of the ion current is not strongly dependent on the total voltage is essential to the operation of this acceleration–deceleration technique because the total accelerating voltage is the parameter which is varied to compensate for the energy lost in the collision chamber. The ion current detected in the analyzer when the accelerator voltage is increased by ΔV is proportional to the product of the incident current and the probability of losing the energy $q\Delta V$ in the stopping cell. Since the ion current does not significantly change its spatial distribution or magnitude as a result of the change in the total accelerating voltage by ΔV, the effective value of the incident current remains constant as ΔV is changed. The relative heights of the various portions of the energy loss spectrum are, therefore, directly related to the probability of losing the corresponding amount of energy. Additional accuracy can be obtained by correcting the observed currents for the effects of changing voltage.

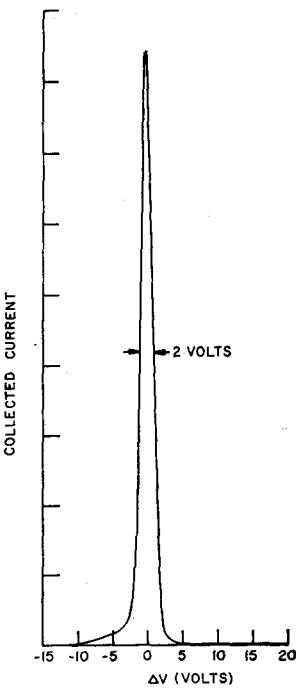

FIG. 5. Incident ion-beam energy distribution.

Resolution

Typical energy resolution is shown by Fig. 5. This is a copy of an energy distribution curve taken with no gas in the stopping cell and recorded directly on the X–Y recorder. The distribution has an energy width at half-maximum of 2 eV. This is comparable with the theoretical width for the analyzer. The source width must also be considered, since the observed energy distribution $\phi(\Delta E)$ is a convolution of the true ion source energy distribution and the apparatus resolution function, which is primarily but not entirely due to the analyzer. The source function cannot be directly determined since it appears to contribute very little to our observed energy distribution. The estimated source width for our system is about 0.2 eV, which includes the effects of the extraction system on the distribution in the source.

Our system compares very favorably with the system of Thread[12] which was designed to measure energy distributions from ion sources and which can therefore be operated under ideal conditions for this purpose. Our observed energy half-width at 50 keV compares favorably with the energy half-width he obtained from his system operated with a beam energy of 690 eV.

Our energy distribution shows a small high energy tail. This tail falls to below 5% of the maximum value at 2.3 eV from the peak and below 1% within 15 eV from the peak. On the low energy side there is almost no tail and the curve falls below 1% of the maximum at 4.5 eV from the peak. The absence of a tail is a result of the design of the Colutron ion source. Thread, using a modified hot-cathode gas-discharge ion source, noted a long low energy tail such that it was necessary to include a region 30 eV wide to include 95% of the area. Ninety-five percent of the area in our zero energy-loss distribution curve is included in a region 5.5 eV wide.

Other sources have been tried in our acceleration–deceleration system. An oscillating electron source was also employed. It had a considerably wierd energy distribution with a large, troublesome, low energy tail. This tail was a strong function of the source magnetic field setting, but it was not possible to set the magnetic field to entirely eliminate the tail without losing the discharge in the ion source.

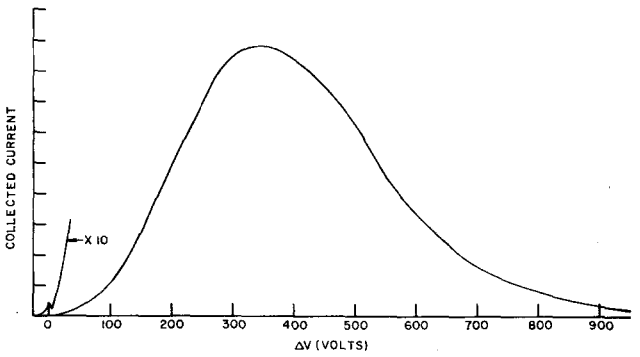

FIG. 6. Energy loss spectrum for 50 keV protons after passing through argon gas. The Ar pressure in the stopping cell was 80.19 μ.

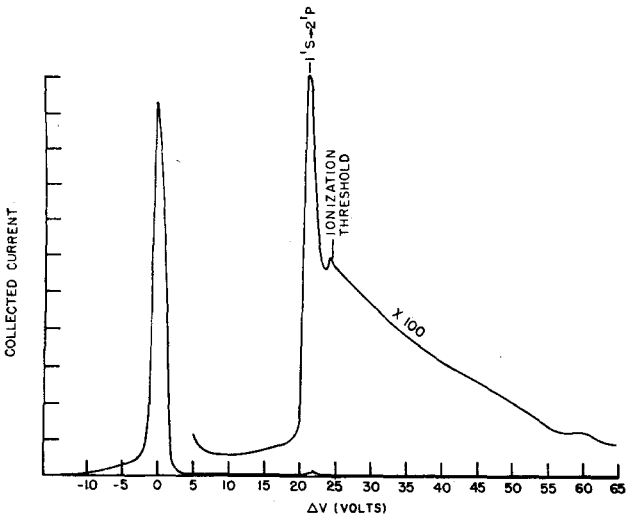

FIG. 7. Energy loss spectrum for 50 keV protons after passing through helium gas. The He pressure in the stopping cell was 3 μ.

Stopping Power

The stopping power of a gas in terms of the energy loss cross section per molecule is $\epsilon = (1/N)(\Delta E/\Delta x)$. ϵ is given in units of 10^{-15} eV·cm^2/molecule. Δx is the effective path length and N is the number of molecules/cm^3. The energy loss ΔE is usually determined by measuring the most probable loss in energy of the singly ionized fraction of the beam. In this experiment, this is done by measuring the offset voltage necessary to compensate for the energy shift which occurs in the peak of the ion beam distribution as gas is introduced into the stopping cell. The stopping power is measured with the gas pressure in the stopping cell high enough to assure that the beam is in charge equilibrium. It is the energy loss cross section for a charge equilibrated beam which has undergone many collisions.

Preliminary data for protons incident on argon gas are shown in Fig. 6. This is a copy of data taken directly from the X–Y recorder. Notice that with the gas pressure at 80.19 μ the incident beam profile is still quite discernible at high sensitivities. It is clear that the most probable value of ΔE can be measured to an extremely high degree of accuracy. The peak in the initial and final distributions can be accurately determined and the change in the ΔV readings, which is directly proportional to the most probable energy loss, measured.

It can be shown that for small energy losses the most probable and the mean energy losses are not identical. It is necessary to obtain an accurate display of the exit

[12] L. P. Thread, Rev. Sci. Instrum. **39**, 1639 (1968).

beam distribution to determine the average energy loss, which is usually the parameter of interest. The additional accuracy of this apparatus will permit making adjustment for the asymmetrical exit beam distribution and, in particular, the data can be analyzed by the computer and the mean energy loss readily calculated from the curve shapes. Both the most probable and the average energy loss cross section can therefore be obtained from the data.

The experimental arrangement permits the accurate measurement of very small energy losses and hence the measurement of the energy loss for a large range of pressure variation. The cross sections can be determined as a function of pressure, making it possible to calculate the energy loss cross sections under single collision conditions for the charged ion beam. These partial stopping power measurements would include only processes which do not involve a charge change for the ion.

Energy Loss Spectra

Raw data under single collision conditions are shown in Fig. 7. The incident beam distribution had a 2 eV half-width. The pressure of helium gas in the cell was 3 μ. The resulting curve is a copy of the curve plotted by the X–Y recorder using the method outlined above. The region of the first excitations and ionization is also shown at high sensitivity (100×) after subtracting the primary beam distribution. The primary peak is due to transmitted protons. The particles having undergone inelastic energy loss by collisions with the gas are just distinguishable as a tiny bump on this scale. When the sensitivity is increased by 100 the features of the inelastic energy loss curve are readily visible. The $1^1S \rightarrow 2^1P$ transition in helium is known to occur at $\Delta E = 21.22$ eV from spectoscopic and electron impact data. This peak is conclusively identifiable in the proton energy loss spectrum. The next lower peak in the energy loss spectrum curve is due to transitions to the 3, 4, 5, 6^1P, and higher order states which, due to the close spacing of these states, are unresolved with the present apparatus. This series of excitations blends smoothly into the ionization continium.

A suggestion of the $(1s)^2\ ^1S \rightarrow (2s2p)^1P$ transition corresponding to the simultaneous excitation of two helium electrons with an inelastic energy loss of 60 eV can be noted in Fig. 7. Additional work must be done before this transition can be conclusively identified by this method.

Discussion

Using the information included in the ion distributions shown above, it should be possible to resolve lines separated by much less than 2 V. The resolving power of this system by the well known Rayleigh criterion is 2.5×10^4. This criterion makes use of only a few points on the distribution. Since the energy distributions both with and without gas in the stopping cell are available, all the points on the curves can be used to determine the measured spectrum. The observed energy loss spectrum is actually a complex convolution of the line spectrum with the energy distributions of ions from the source, and a general apparatus function. Mathematical methods[13] have been developed to determine the actual spectrum by deconvolution of the experimental curves. Other mathematical processes have been developed to determine the probability of a correct decision.[14] The detectable differences between two possible spectra depend on the variance of the noise as well as the widths of the lines and their separations. The observed energy spectra are relatively free from noise, hence the actual resolution of the acceleration–deceleration system in terms of its ability to determine the correct energy loss spectrum after deconvolution is therefore much greater than that suggested by the Rayleigh criterion.

With the present resolution it should be possible to measure the proton-induced excitation cross section for the $1^1S \rightarrow 2^1P$ transition in helium and the cross section for energy loss $\sigma(\Delta E)$ as well as the stopping power and partial stopping powers for protons passing through gaseous targets. Work is now underway to make accurate energy loss spectrum measurements on a range of gases. At the same time a continuing program is dedicated to increasing the effective resolution of the system.

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