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MEASUREMENT OF THE IONIZATION YIELD
OF LOW ENERGY ATOMIC PARTICLES IN
GASES

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MEASUREMENT OF THE IONIZATION YIELD OF LOW
ENERGY ATOMIC PARTICLES IN GASES*

by
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ABSTRACT

The purpose of this investigation was to study the total ionization yield of charged atomic particles in gases for energies in the range of a few to 250 kev. A large cylindrical ionization chamber was used for this study. The charged particles were selected from the kevatron beam by a magnetic and an electrostatic analyzer and entered the chamber by means of a 0.004 inch diameter open window. A differential pumping system permitted pressures up to 10 mm Hg to be maintained in the chamber. The chamber was alternately operated as a proportional counter and an ionization chamber to measure the rate with which the primary ions entered the chamber and the ionization produced by them, respectively. A detailed description of the apparatus and measuring technique are given.

The ionization yields of protons in nitrogen were measured as a preliminary test of the feasibility of the experimental method and to check the performance of the apparatus. The results of these measurements were subject to large uncertainties but indicated a straight line relation between ionization yield and energy for energies above 75 kev. The slope of the line corresponded to 36.6 ev/ip.

More precise measurements were made of the ionization yield of protons in argon. The results indicated that any deviation from a linear relation between ionization yield and energy was small for energies above 25 kev. The slope of a least squares plot of the data corresponded to 26.5 ev/ip. The straight line representing the least squares plot intercepted the energy axis at 1.4 kev indicating a slight ionization defect for protons in argon.

It was concluded that the apparatus and measuring technique had proven to be relatively successful and perhaps adequate to continue with an investigation of more interesting combinations of ions and gases.

*This report is based on a Ph.D. thesis by Ralph A. Lowry submitted June, 1955, to Iowa State College, Ames, Iowa. This work was done under contract with the Atomic Energy Commission.

INTRODUCTION

Ionization of gases by charged atomic particles has been studied both experimentally and theoretically for many years, especially in regard to the relation between the energy of the particle and the total ionization produced. The total ionization produced has often been used as a means of determining the energy of a charged particle. Much of the experimental work in this field has been concerned with the light nuclear particles: alpha particles, protons, and deuterons. In most cases these particles were produced by natural radioactive sources or by induced nuclear reactions; consequently, the energies of the particles were generally above 0.5 Mev.

There has also been considerable interest in the ionization yield of lower energy particles, particularly heavier atomic particles such as argon ions. Ionization is one of the fundamental energy loss processes for charged particles and it is in this low energy region that the competing process of elastic scattering becomes significant. Much attention has recently been given to the ionization yield of low energy recoil gas atoms such as those produced by neutrons on one extreme and by fission fragments on the other. The ionization yield of a fission fragment may depend considerably upon the secondary ionization by recoil gas atoms. Likewise, radiological effects are brought about, in part, by the ionization produced by low energy recoil atoms. Accordingly, there is a demand in these fields for further information on the ionization yield of low energy ions.

Experimental results for the ionization yield of atomic particles in the lower energy region are extremely few and contradictory. This has been due largely to experimental difficulties and inadequacies in available experimental methods. The need for further measurements in this low energy region was apparent. Accordingly, it was the purpose of the work reported herein to develop the apparatus and a technique for the measurement of the ionization yield of charged atomic particles in gases for energies in the range of a few to 300 kev. Preliminary studies were made of the ionization yield of protons in nitrogen and argon gases. This work was considered a prelude to a continued investigation of the ionization yield of hydrogen, helium, nitrogen, and argon ions in hydrogen, helium, nitrogen, air, argon, and possibly other gases. Eventually, it would be of interest to proceed to a study of the differential ionization yields. From the results of the differential measurements, the cross section for total ionization could be determined.

SURVEY OF LITERATURE

A. Energy Loss by Charged Particles Passing through a Gas

An excellent comprehensive review of both the theoretical and experimental aspects of energy loss by charged particles passing through matter has been presented by Bethe and Ashkin (1). A more recent survey of experimental results has been published by Allison and Warshaw (2). Theoretical discussions by Bohr (3) give more attention to extremely low velocity and much heavier particles.

The three primary mechanisms by which a fast charged atomic particle loses its energy as it passes through a gas are briefly summarized below. In the discussions which are to follow, reference to the velocity of the incident particle will, in general, be relative to the velocity of the electron in the first Bohr orbit of the hydrogen atom,

$$v_0 = e^2/h = 2.2 \times 10^8 \text{ cm/sec.}$$

Thus, a high velocity particle will imply $v \gg v_0$ and a very low velocity particle, $v \ll v_0$.

1. Elastic collisions

When an energetic charged particle is scattered by the nuclear coulomb field of a gas atom, the atom recoils and takes away part of the energy. This mode of energy loss becomes significant only at very low velocities and depends upon the maximum energy transfer possible. The frequency of such collisions is governed by the well-known Rutherford scattering formula.

2. Charge exchange

An ion moving with a velocity comparable to the velocities of its own orbital electrons will continually capture and lose electrons. The net effect of one capture-loss cycle is that one gas atom has been ionized. Hence, the primary ion must have lost at least an energy equal to the first ionization potential of the gas. The extensive experimental and theoretical literature on the capture and loss of electrons has been reviewed by Allison and Warshaw (2). The general theoretical principles are discussed by Bohr (3).

3. Inelastic collisions

At energies for which the velocity of the incident particle is large, inelastic collisions with the gas atoms resulting in excitation and ionization account for practically all of the energy loss. The slowing down process in this energy region has been theoretically treated by Bethe (4). Bethe's treatment of the energy loss is based on the Born approximation applied to collisions between the heavy particle and the atomic electrons. However, when the charged particle is slow enough to capture electrons the theoretical problem becomes extremely difficult.

B. Ionization Theory

The most practical aspect of ionization studies is the relation between the total ionization yield and the energy of the incident particle. The quantity of the greatest practical importance is the average energy per ion pair W which is obtained by dividing the total energy E of the incident particle by I the total number of ion pairs produced:

$$W = E/I .$$

A theoretically more significant quantity is the energy W' per ion pair for a small change in particle energy:

$$W' = dE/dI .$$

A proposed ionization yield curve is illustrated in Fig. 1. At sufficiently high energies, W' approaches a constant value. In this energy region the energy of the incident particle may be expressed by the simple relation

$$E = E_0 + W'I , \quad (v \gg v_0) .$$

The quantity E_0 is sometimes referred to as an ionization defect and is a function of both the gas and the type of incident particle.

The contributions to the total ionization yield of a charged particle may be distinguished as either primary or secondary. The ionization produced by direct collisions between the incident particle and the electrons of the gas atoms will be referred to as primary ionization, whereas ionization resulting from other processes will be designated as secondary ionization.

1. Primary ionization

The primary ionization yield depends on the ionization cross section for the incident particle and includes ionization resulting from charge exchange. Calculations of the cross sections for primary ionization have been made for hydrogen atoms by Bethe (4). More recently Bates and

FIG. 1 RELATIVE IONIZATION YIELD OF A CHARGED PARTICLE IN A GAS

Griffing (5,6,7) have computed the cross sections for excitation and ionization of hydrogen atoms by protons and hydrogen atoms. Moiseiwitsch and Stewart (8) have published theoretical cross sections for excitation of helium atoms in fast encounters with hydrogen atoms, protons, and helium ions. The results of these calculations illustrate excitation and ionization as competing processes of energy loss. At high velocities the ratio of the energy losses by the two processes approaches a constant value for a given gas and does not vary significantly for different particles of the same velocity. However at lower velocities the ratio of ionization to excitation losses does not remain constant and at sufficiently low velocities may result in a significant variation of W' with energy. However, such conclusions remain speculative until further calculations are made or additional experimental results become available.

At very low velocities where the ionization cross section is decreasing rapidly with energy, the competing process of elastic collisions between the incident particle and the gas atoms becomes of increasing importance and will eventually dominate as a mode of energy loss. At intermediate velocities, charge exchange may become an important mechanism for ionization and energy loss. The effect of charge exchange becomes negligible at extremely high velocities and extremely low velocities since under these conditions the incident particle is either completely charged or completely neutral, respectively. For a particle with a large nuclear charge such as a fission fragment, charge exchange may occur over most of its range.

2. Secondary ionization

When a charged particle is stopped in a gas, further ionization may be produced by secondary processes. Such processes include ionization by electrons ejected by primary collisions, ionization by recoil gas atoms, and ionization by atomic collisions of the second kind.

In every primary ionization collision between a charged particle and an atom, one or more electrons are ejected. A small fraction of these electrons will have energies greater than the ionization potential of the gas and will be responsible for most of the secondary ionization. To estimate this secondary ionization it is necessary to examine the number and energy distribution of the electrons ejected in primary collisions. Such distributions have been discussed by Bethe and Ashkin (1) and have been specifically calculated for protons in hydrogen by Bates and Griffing (5). The maximum energy of the ejected electrons will be approximately $4(m/M)E$ corresponding to a maximum velocity of twice the velocity of the incident heavy particle.

The significance of secondary ionization by recoil gas atoms has been discussed by Knipp and Ling (9). When the velocity of the incident particle falls below a velocity of the order of v_0 , energy loss to recoiling atoms

predominates. Ionization then proceeds by means of secondary ionization arising from recoil atoms. If the efficiency of ionization for these secondary heavy particles is low, the over-all efficiency for the production of ion pairs is greatly reduced. A very heavy particle such as an argon ion, with a velocity of v_0 , has an energy of the order of a million electron volts, whereas a proton of this velocity has an energy of 25 kev. Hence, the energy which fails to give rise to ionization for a heavy particle can be rather large if the efficiency of ionization by recoil gas atoms is low. The efficiency of the recoil particle will depend on the energy transferred to it. The maximum energy transferred in an elastic collision is

$$E_{M'} = 4MM'E/(M + M')^2$$

where M and M' are the masses of the particle and gas atom, respectively.

Generally, atomic collisions of the second kind are significant as a source of secondary ionization only in the case of gas mixtures where the ionization potential of one gas is less than the excitation levels of the other. Collisions of the second kind involve the transfer of potential energy of excitation from one of the interacting particles to the other. They can be represented by the equation

where the starred letter represents atoms in some excited state, and δ is the so-called energy discrepancy. If the ionization potential of the second gas atom is less than the excitation energy of the other then ionization may result:

Jesse and Sadauskis (10,11) have discussed the importance of this process in producing secondary ionization in mixtures of noble gases. Here the ionization results from a transfer of energy from the metastable states of one noble gas to the atoms of another noble gas or to the atoms of some contaminating gas. Cross sections for collisions of the second kind can be calculated approximately, and are discussed by Massey and Burhop (12). Similar types of collisions resulting in ionization can occur between an excited or ionized gas atom and the chamber walls or the surfaces of the electrodes. This phenomenon has also been discussed by Massey and Burhop (12).

C. Survey of Experimental Results

Literature upon the subject of experimental investigation of the ionization yield of energetic charged particles in gases is extremely voluminous. A review of the experimental results up to 1944 has been

given by Gray (13), and a more recent summary may be found by Bethe and Ashkin (1). Massey and Burhop (12) have discussed the experimental results for very low energy ions. Many contradictory results are found in the literature. Perhaps the most significant work in regard to clarifying this highly confused subject has been that of Jesse, *et al.* In 1950, Jesse, Forstat, and Sadauskis (14) provided evidence that for alpha particles in the energy range of 1 to 9 Mev there was no measureable change in the average energy per ion pair in argon. They compared this with the alpha ionization in air from the work of Stetter (15) which showed a marked increase in W as zero alpha energy was approached.

Jesse and Sadauskis (10) also established the importance of the effect of minute quantities of impurities in noble gases and accounted for this effect by atomic collisions of the second kind. Jesse and Sadauskis (11) have made precise measurements of W for alpha particles in carefully purified samples of the five noble gases, air, carbon dioxide, hydrogen, oxygen, nitrogen, and several hydrocarbons. The average energy per ion pair for alpha particles in many of these same gases has been measured by Bortner and Hurst (16); Sharpe (17); Valentine and Curran (18); Haeberli, Huber, and Baldinger (19); Bertolini, Bettoni, and Bisi (20); and Herwig and Miller (21). The ionization yields of alpha particles in mixtures of gases have been measured by Bertolini, Bettoni, and Bisi (22); Bortner and Hurst (16); and Melton, Hurst, and Bortner (23).

Recently, Curtis (24) has investigated the ionization yield of the particles from the reaction $B^{10}(n, \alpha)Li^7$ relative to the Po alpha particle. The energies of the alpha and Li recoil were 1.47 and 0.84 Mev, respectively. This investigation was carried out for pure argon and argon plus small percentages of carbon dioxide and nitrogen. In pure argon the results for the alpha particle showed no deviation from a proportionality between the energy and ionization but there was evidence of a slight deviation in the gas mixtures. However, for the Li recoil there was a definite deviation for all three gases, being smallest for pure argon and largest for argon plus carbon dioxide. These results were compared with those of Hanna (25); and Rhodes, Franzen, and Stephens (26) who also studied the ionization yield of this reaction in argon plus a small percentage of carbon dioxide. The results of these latter investigations indicated a departure from linearity in the relation between ionization and energy. Facchini, Gatti, and Germagnoli (27) studied the ionization yield in purified argon of the particles from the reaction $Li^6(n, \alpha)H^3$ in which the alpha particle has an energy of 2.06 Mev and the triton an energy of 2.75 Mev. Their results verified a linear relation between ionization and energy.

Franzen, Halpern, and Stephens (28) measured the total ionization produced by the reactions $He^3(n, p)$ and $N^{14}(n, p)$ in a gas mixture consisting mainly of argon. The reaction energies were 766 and 630 kev, respectively. Comparison with Po alpha particles supported the assumption of a proportionality between energy and the ionization in argon independent of particle

type. Leachman (29), Herwig and Miller (30), and Schmitt (31) have studied the relative ionization yield of fission fragments and, in general, agree that the ionization yield depends upon the mass of the particle, being different for the light and heavy fragment. The average energy per ion pair was found to be higher for these heavy particles than for alpha particles and the ratio depended on the type of gas.

In the 1944 review by Gray (13) the works of Jentschke (32) and Gerthsen (33) were the most pertinent to the present experiment. Jentschke investigated the specific ionization-range relation in nitrogen for individual protons with ranges between 10 and 70 cm. By integrating to get the total ionization and then extrapolating this result to air, he obtained 35.9 ev as the average energy per ion pair for 7.56 Mev protons. Gerthsen measured the total ionization of proton beams with energies in the range of 27 to 45 kev and noted no departure from 36 ev/ip for the value of W in air. Gerthsen also found that the ionization yield in hydrogen for protons in this same energy range was about the same as in air. Measurements by Stetter and Jentschke (34) for 470 kev protons in hydrogen gave 32.6 ev/ip. Gray combined these results with some data for photo-protons from deuterium and concluded that for energies above about 25 kev the average energy per ion pair for protons in hydrogen was 35 ± 1.5 ev.

Tunncliffe and Ward (35) studied the relative ionization yield of protons, deuterons, and alpha particles by means of a proportional counter filled with a mixture of argon and methane. The energetic particles were produced as neutron recoils. From the results it was inferred that for protons with energies between 200 and 500 kev the ionization was proportional to the energy. For energies between 200 and 400 kev the total ionization produced by protons in argon was about 8 percent greater than that of alpha particles of equal energy. The range of particle energies investigated was not large enough to prove conclusively that the value of W was also a function of particle energy, although the results favored this interpretation.

Massey and Burhop (12) have summarized the experimental data available on cross sections for ionization by positive ions and neutral atoms with energies within the near adiabatic region, $v < v_0$. Ionization cross sections for helium atoms and ions in helium have been measured by Rostagni (36), Berry (37), Rudnick (38), and Keene (39). Measurements of the ionization cross sections of rare gas atoms by collisions with their own ions have been made by Rostagni (36), Berry (37), and Batho (40) and for argon ions in hydrogen by Wolf (41). Although there was large disagreement in the absolute magnitude of the results of various investigators, their results agreed in giving cross sections with consistent variation with relative velocity. The most recent measurements in this near adiabatic region have been by Keene. He investigated the ionization cross sections for hydrogen and helium ions in hydrogen and helium in the energy range of 3 to 35 kev. The probable errors were somewhat large; 15 percent for ions in hydrogen and 20 percent for ions in helium.

EXPERIMENTAL METHOD

Several difficulties were encountered in the development of a successful technique for measuring the ionization yield of atomic particles with energies below 300 kev. The first of these problems was that of getting the low energy particles into an ionization chamber. In cases where studies have been made with alpha particles, neutron recoils, or particles from nuclear reactions, the sources of particles were usually contained within the ionization chamber. However, in order to investigate this low velocity region over a continuous energy range, it was necessary to resort to an ion accelerator as a source of charged particles. Large energy losses, straggling, and contaminating deposits of pump oil discouraged the use of windows of thin foils or organic films. Consequently, it was proposed that the primary ions be admitted into the ionization chamber by means of an open window. This required the use of a continuous flow chamber which had to be operated at very low pressure.

A second problem concerned the measurement of the small quantity of ionization produced by charged particles below 300 kev. The method which is generally employed for particles above 0.5 Mev consists of studying individual particles by collecting their ionization on isolated electrodes and measuring the change in potential of these electrodes.* This potential change is usually observed as a voltage pulse of height

$$V = q/C$$

where q is the ionization produced by a single particle and C is the capacitance of the electrode. However, at lower energies the charge collected would be too small to permit the height of the pulse to be determined accurately. For example, the pulse height for a 50 kev proton, where C is 33 micromicrofarads and W is 30 ev/ip, would be approximately 8 microvolts. This is of the same order of magnitude as the noise at the input of most pulse amplifiers which are used with ionization chambers. There are two ways to obtain a quantity of charge which can be measured with a satisfactory degree of precision. One such way would be to multiply the ionization as is done in a proportional counter. The other way would be to integrate the ionization produced by several particles. For the experiment at hand the latter method was chosen since it did not require knowledge of the elusive multiplication factor for the chamber and gas. The choice of this method, however, introduced another difficulty.

*Very comprehensive accounts of the principles of operation and construction of ionization chambers and counters have been published by Wilkinson (42), Rossi and Staub (43), and Corson and Wilson (44).

Since a single particle was no longer being studied it was necessary to determine the number of particles producing the ionization which was measured.

Several alternate methods of determining the incident particle rate were tried. The ionization chamber was isolated and used as a Faraday cage whereby the net current into it was proportional to the incident particle rate. However, this method had two serious difficulties associated with it. It was necessary to know the average charge of the incident particles as they entered the chamber. The charge state of an ion has been found to be a function of its energy and the type of gas.* Furthermore, it was extremely difficult to distinguish between the primary particles and the secondary particles which were present in the vicinity of the open window. Failure to eliminate the effects of these secondary charged particles caused this method of measurement to be discarded. Another method consisted of establishing a correlation between the current to a beam stop in front of the entrance to the chamber and the rate at which the incident particles entered the chamber. This method was tried briefly but without success. Since the beam stop and aperture were later found to be improperly aligned, this method might warrant further investigation. The method which was finally adopted for determining the incident particle rate consisted of detecting and counting individually the particles which entered the chamber. This, of course, assumed that the low energy secondary particles would not be detected. Some of the devices which were considered for detecting and counting the incident particles were an electron multiplier, a scintillation counter, and a proportional counter. Although there were advantages to each of these methods, the idea of using a proportional counter was more readily adaptable to the proposed experimental arrangement. It was possible to operate the ionization chamber alternatively as a proportional counter.

The experimental method may be summarized as follows: A beam of ions of known energy from the kevatron was admitted into the ionization chamber through a 0.004 inch diameter open window. The chamber was cylindrical with the center electrode off center. The electrons and negative ions produced in the ionization processes were collected on the outer electrode and measured as a current with a vibrating reed electrometer. To determine the rate at which the primary ions entered the chamber, it was operated alternately as a proportional counter by which each primary particle entering the chamber was detected and counted. Thus, the ionization yield Y (in coulombs per primary ion) was computed by the

*Some recent experimental studies of the charge states of ion beams in gases have been made by Ribe (45), Kanner (46), Snitzer (47), and Stier, Barnett, and Evans (48).

equation

$$Y = \frac{\text{ionization current}}{\text{count rate}},$$

and the average energy per ion pair

$$W = \frac{E \times 1.6 \times 10^{-19}}{Y} \quad (\text{ev/ip}),$$

where E was the energy of the incident particle in electron volts.

APPARATUS

A. Kevatron

The ion beams studied in this experiment were produced by the kevatron, a 300 kv linear dc accelerator. The accelerating potential was supplied by a cascade of two conventional doubling circuits. This potential could be continuously varied from 0 to 300 kv by a variable auto-transformer which supplied the primary voltage. When the kevatron was operated at 150 kv and with a beam current of less than 0.1 ma, the ripple on the accelerating potential was observed to be about 500 volts and predominantly 120 cps. As the beam current was increased to 0.6 ma the ripple increased to about 700 volts.

The stability of the accelerating potential required considerable attention. The ac line voltage, although supplied from a 220 volt Stabiline regulator, was not sufficiently constant at times. For potentials above 200 kv, the corona from the high voltage supply became very troublesome. There were apparently other undetermined sources of instability.

A reasonably successful attempt was made to automatically regulate the kevatron energy. A schematic diagram of the regulating system is shown in Fig. 2. An error signal was derived from an insulated exit slit assembly for the magnetic analyzer. When the energy of the beam changed, the current to the two sides of the slit became unbalanced. The resulting difference in potential of the two slit plates was amplified with a dc difference amplifier (49). This signal was used to control the saturating current in the saturable core reactor which in turn could be used to control an increment of the primary voltage of the high voltage supply. This fine control of the accelerating potential was accomplished by installing a filament transformer with its secondary winding in series with the output of the main control auto-transformer. The primary current of the filament transformer could be controlled either automatically by the saturable core reactor or manually by a variable auto-transformer. This fine control provided a means of very accurately adjusting the energy of the beam.

It was somewhat difficult to give a quantitative evaluation of the performance of the regulator since it depended directly upon the beam conditions. In general, it could be relied upon to keep the average energy constant to within 0.5 percent, being better at low energies than at the higher energies. Since the kevatron beam was seldom centered with respect to the exit slit of the magnetic analyzer, the regulator was sensitive to the beam intensity. This caused the variations in beam intensity to actually be amplified and proved to be a serious disadvantage for this method of regulation.

The focusing and intensity of the beam depended largely upon the ion source (50). The very small beam currents required by the experiment permitted the ion source to be operated with both the probe and first electrode at the potential of the ion source case. Thus, two variables which might have caused the beam intensity to drift were eliminated. Under these latter conditions the drift in the beam intensity was caused almost entirely by variations in the pressure in the ion source or arc conditions. These variations were finally made to be quite small. Random variations in the position and focusing of the beam were often troublesome and warrant further attention.

B. Magnetic Analyzer

The desired ion component of the kevatron beam was selected by magnetic analysis. The magnetic analyzer was of the conventional design used in mass spectrometers (51). The pole pieces were wedge shaped corresponding to an angle of deflection of 27 degrees. The radius of curvature of the ion trajectory was 12.7 inches, the distance from the entrance slit to the virtual pole face was 5 feet, and the distance from the virtual pole face to the exit slit was 4 feet. The theoretical resolving power for slit widths of 0.125 inch was approximately 200.

The magnet coils and current supply were capable of producing a maximum field of approximately 5000 gauss in the 1 inch gap between the pole pieces. This field was sufficient to deflect 0.5 Mev deuterons through the geometrical arrangement specified above. The current control for the magnet maintained the current in the coils constant to within 0.1 percent for periods of 8 hours or more. By varying the current and switching coils the field strength could be varied continuously from 490 to 5300 gauss.

C. Electrostatic Analyzer

The energy of the ion component selected by the magnetic analyzer was determined by means of electrostatic deflection. The electrostatic analyzer (52) deflected the ion beam through a 120 degree arc with a mean radius of 10 inches. This deflection was produced by a radial electric

FIG. 2. SCHEMATIC DIAGRAM OF THE CONTROL SYSTEM AND REGULATOR FOR THE KEVATRON HIGH VOLTAGE POWER SUPPLY.

field between two curved metal plates spaced 0.382 inch apart. The constant for this analyzer was 13.13 ± 0.10 . Thus, an ion having a charge Z and an energy E traversed the analyzer only if the potential between the deflection plates was $E/(Z \times 13.13)$. This constant was calculated from the physical dimensions of the analyzer.* The entrance and exit of the analyzer were defined by 0.05 inch slits which corresponded to a theoretical resolving power of approximately 200. It was possible to increase the resolving power to 1000 by using 0.01 inch slits. However, this caused the beam current entering the ionization chamber to be overly sensitive to instabilities in the kevatron energy.

The deflection plates were operated at equal and opposite potentials supplied by a variable regulated r-f type voltage supply. The regulator maintained the potential difference between the plates constant to within 0.01 percent for periods of several hours after an appropriate warm-up period. The analyzer voltage was determined by means of precision voltage dividers connected in parallel with each deflection plate. Each voltage divider consisted of a 20 megohm precision resistance stack in series with a 775 ohm precision resistor; a potentiometer (Leeds & Northrup type 7551) was used to measure the voltage drop across these resistors. Fig. 3 shows a schematic diagram of the measuring circuit. The over-all calibration constant for the electrostatic analyzer, computed from the physical dimensions of the deflection plates and the ratio of the voltage divider, was 348,700 with respect to the voltage difference between points A on the two dividers.

D. Ionization Chamber

1. Construction

The low pressures at which the ionization chamber was operated due to the open window, required that the chamber be rather large in order to stop the ions investigated. The extreme case was that of protons in hydrogen. The experimental data of Cook, Jones, and Jorgensen (53) indicated that the range of a 241 kev proton in hydrogen would be 73.9 cm at a pressure of 10 mm Hg. Since the lower energies were of the greatest interest and the stopping powers of the other gases used were greater, a chamber with an effective stopping length of 75 cm was considered sufficient to stop all ions of interest.

A schematic drawing of the ionization chamber and the differential pumping section is shown in Fig. 4. The ionization chamber was cylindrical

*This constant was being checked at the time of writing by Phipps (52) using the 163 kev resonance in the $B^{11}(p,\gamma)$ reaction.

FIG. 3 SCHEMATIC DIAGRAM OF ELECTROSTATIC ANALYZER AND CIRCUIT FOR MEASURING THE DEFLECTION VOLTAGE

with a diameter of 10 inches and an over-all length of 41 inches, and was constructed mostly of brass. The stainless steel outer electrode was 9 inches in diameter and 40 inches long, being insulated from the chamber walls by fluorothene rings. The end of the outer electrode next to the differential pumping section fitted upon the aperture assembly (not shown in Fig. 4) and thereby was completely closed except for a 0.0625 inch hole by which the beam entered. The other end was only partially closed with a ring having an inside diameter of 7 inches. The outer electrode could be easily removed from the chamber by first removing the end plate of the chamber. An electrical connection was made to the outer electrode by way of a vacuum tight fluorothene feed-through insulator in the chamber wall. Fluorothene was used for electrical insulation throughout the chamber because of its high resistivity, low vapor pressure, and good machinability.

Two different center electrodes were used during the investigations. One was made of aluminum, 0.25 inch in diameter with a 0.5 inch diameter sphere on the end. However, for the final studies in nitrogen and argon, the part extending into the effective stopping region was made of stainless steel, 0.125 inch in diameter with a 0.25 inch diameter sphere on the end. This stainless steel part telescoped into a 0.25 inch diameter aluminum support which extended nearly half the length of the chamber. The smaller diameter electrode gave better multiplication for proportional counter operation and still permitted saturation to be attained when the chamber was used for current measurements. The center electrode was supported from the end plate by means of a fluorothene feed-through insulator. This electrode was located one inch off the axis of the chamber so it would not be directly in the path of the ion beam. The other end of the center electrode was 2.5 inches from the end of the outer electrode and was supported from the top of the outer electrode by means of a silk thread. The feed-through insulator supporting the center electrode was shielded from the radiation and light in the chamber by a 3 inch diameter aluminum disc fitted on the coupling directly in front of it.

Openings were provided in the chamber walls for connections to an ionization gauge, a manometer, a gas purifier, and for direct evacuation through the differential pumping section. Teflon gaskets were generally used where demountable vacuum seals were required. A heating element was wound around the outside of the chamber to facilitate outgassing during evacuation. The chamber and differential pumping section were supported by means of a carriage constructed of angle iron. One inch diameter bolts in the base of the carriage were used to level and adjust the height of the chamber.

2. Aperture

The aperture assembly is shown in detail in the drawing of Fig. 5. The end of the outer electrode was about 0.125 inch from the aperture plate and insulated from it. In order to collect all of the ionization

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FIG. 4 CONTINUOUS-FLOW CURRENT IONIZATION CHAMBER

produced in the gap between the aperture and the outer electrode, it was necessary to apply a potential of a few volts to the outer electrode. An insulated beam stop with a 0.03 inch diameter hole, mounted 0.187 inch in front of the aperture, provided a means of monitoring the incident beam. In the design of this assembly an attempt was made to keep the energy loss at a minimum in the regions where the ionization could not be collected, such as in the aperture itself. The diameter of the hole in the outer electrode was made large enough so that essentially all the ions passing through the aperture would also pass through the hole in the outer electrode. Calculations of the elastic scattering of 50 kev protons in argon at a pressure of 10 mm Hg indicated that less than 2.4 percent of the protons were lost in the region between the aperture and outer electrode.

The alignment of the aperture and the beam stop was found to be extremely critical. This tedious task of alignment was accomplished by sighting through the aperture assembly toward the small filament in a 1.5 volt lamp which was held in front of the exit slit of the electrostatic analyzer. The final adjustments in the position of the chamber and differential pumping section were made after the chamber had been assembled and a beam had been deflected into it.

3. Differential pumping

The flow of gas through the aperture necessitated the use of differential pumping between the ionization chamber and the high vacuum system of the electrostatic analyzer. This permitted the chamber to be operated at pressures up to 10 mm Hg. The differential pumping section was evacuated with a National Research H-6 diffusion pump, type 104, which had a pumping speed of approximately 600 l/sec at a pressure of one micron Hg. The variation of the pressure in the differential pumping section with the pressure in the ionization chamber is illustrated by the graph in Fig. 6 for argon gas.

A liquid nitrogen cold baffle was installed in the differential pumping section to reduce the concentration of pump oil in the vicinity of the aperture. This baffle was necessary to prevent the aperture from becoming stopped with droplets of oil. Its construction was similar to the cold trap described by Miller (54) and was supported from the top of the differential pumping section by two stainless steel filling tubes. Both a Pirani and an ion gauge were attached to the pumping section for measurement of the pressure in it.

The ion beam entered the pumping section through a long projecting tube, 0.75 inch in diameter. At the end of the tube there was a canal, 0.125 inch in diameter and 1 inch long. The entrance and exit of the tube were defined by beam stops with holes 0.125 and 0.05 inch in diameter, respectively. The purpose of this projecting tube was to extend the high vacuum path of the ion beam.

FIG. 5 SCHEMATIC DIAGRAM OF THE APERTURE ASSEMBLY

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FIG. 6 PRESSURE IN DIFFERENTIAL PUMPING SECTION
AS A FUNCTION OF IONIZATION CHAMBER PRESSURE

4. Gas filling system

The gas filling system is illustrated by the schematic diagram in Fig. 7. The gas from the tank passed through a dry ice cold trap and was admitted into the chamber by means of a thermal valve similar to the one described by Billings and Mossman (55). The gas entered the chamber through a hot calcium purifier operated at 300 to 350 degrees C (used only for argon gas). A drawing of the purifier is shown in Fig. 8. It consisted of a vertical stainless steel tube with connections to the chamber at the bottom and top so that when the tube was heated convection currents caused the gas in the chamber to circulate through it. Between the heated section and the openings going into the chamber, short lengths of the tube were machined to a wall thickness of 0.01 inch. This reduced the heat conduction sufficiently to eliminate the necessity of water cooling the connections between the purifier and the chamber. The new gas was admitted into the purifier through a small tube soldered into the bottom and extending up into the center of the purifier. The basket for the purifying material was soldered to the thermometer well and could be easily removed through the top of the purifier.

A charcoal cold trap was also installed in such a manner that the gas in the chamber would circulate through it. However, it proved to be improperly designed for the pressures at which the chamber was operated and was not used during any of the studies reported herein.

5. Pressure regulator

An automatic pressure regulating device (56) was developed to maintain a given pressure in the chamber over the long periods required for the measurements. The pressure monitor is illustrated by the schematic diagram in Fig. 9. It consisted of an oil manometer, a light source, and two phototubes. When the manometer arms were filled with oil they acted as cylindrical lenses, focusing the light strongly upon the cathodes of the phototubes. Hence, any change in pressure resulted in more light being focused on one cathode and less on the other. Thus, an electrical signal was derived which was approximately proportional to the change in pressure. This electrical signal from the phototubes was amplified with a dc amplifier and then used to control the saturating current in a saturable core reactor which in turn controlled the power to the thermal flow valve as indicated by the block diagram in Fig. 10. A dry ice cold trap was installed between the ionization chamber and the manometer to keep oil vapors from entering the chamber. The other arm of the manometer was evacuated through the differential pumping section.

6. Electrical fields in chamber

The cylindrical geometry and eccentricity of the electrodes gave rise to highly nonuniform electrical fields in the chamber. The limits for these

FIG.7 SCHEMATIC DIAGRAM OF GAS FILLING SYSTEM FOR IONIZATION CHAMBER

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FIG. 8 ASSEMBLED SECTION OF GAS PURIFIER FOR CURRENT IONIZATION CHAMBER.

FIG. 9 SCHEMATIC OF MANOMETER AND PHOTOTUBE ASSEMBLY FOR PRESSURE REGULATOR

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FIG. 10 PRESSURE CONTROL SYSTEM FOR CONTINUOUS-FLOW IONIZATION CHAMBER

fields were established by calculating the extreme field strengths at both the center and outer electrodes. These calculations were based upon the method of image line charges as discussed by Smythe (57) and were approximate in that they assumed electrodes of infinite length. The results of the calculations are given in Table 1.

Table 1. Electrical fields in the chamber

Maximum field at center electrode	1.50
Minimum field at center electrode	1.49
Maximum field at outer electrode	0.0325
Minimum field at outer electrode	0.0132
Maximum field at end of center electrode	3.32

The values given are the electrical fields in volts per cm per volt of potential difference between the center and outer electrodes. A very approximate calculation was made to estimate the maximum field at the end of the center electrode. The value obtained from this calculation is shown as the last entry in Table 1.

E. Amplifiers

The pulses which originated in the chamber when it was operated as a proportional counter were first amplified with a minimal noise preamplifier similar to the one described by Enslein and Brainerd (58,59). The complete circuit diagram is shown in Fig. 11. The original circuit was modified to reduce the gain to about 500 and to alter the frequency response. The frequency response was changed by direct coupling the fourth and fifth stages and shunting the plate resistor of the fourth stage with a small capacitor. The over-all frequency response after these modifications is shown in Fig. 12. The high gain at low frequencies was undesirable because of the microphonic signals from the chamber. However, these signals were severely attenuated by sharply clipping the signals at the input of the main amplifier. The rms noise of the preamplifier with respect to the input was about 10 microvolts.

FIG. II MINIMAL NOISE PREAMPLIFIER

FIG.12 FREQUENCY RESPONSE OF PREAMPLIFIER

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The main amplifier was a Los Alamos Model 100 amplifier (49) with the input adapted to delay-line clipping. The input of the amplifier and the delay-line pulse-shaping network are shown in Fig. 13. The parameters in the pulse-shaping network were empirically adjusted to make the duration of the pulses as short as possible thereby minimizing the resolving time of counting. The value of the components used for studies in nitrogen and argon are given in the diagram.

F. Scalers

The pulses from the amplifier were recorded by two scalars operated in parallel. One was a binary scalar which had a resolving time of approximately 0.25 microseconds and a scale factor of 8192. The other was a decade scalar with a resolving time of about 1.5 microseconds and a scale factor of 10,000. The voltage hysteresis in the discriminator of both scalars was about 5 volts. The decade scalar was the one generally used for counting during an ionization yield measurement. The two were operated in parallel only during the procedure to determine the proper discriminator settings or to merely check their relative performance.

G. Electrometer

Three different electrometers were used during the course of this experiment. The first one used was a vacuum tube electrometer which employed a Victoreen 5800 electrometer tetrode at the input. It was a dual channel electrometer which had been designed and constructed by the Electronic Shop (60). Each channel had seven current ranges between 10^{-6} and 10^{-12} amperes full scale. This electrometer was used for much of the preliminary work with hydrogen and nitrogen. However, it proved to have three significant disadvantages: its lack of stability required that the calibration be checked and the zero adjusted often; it was slightly non-linear; and its sensitivity was low. A one volt signal was required at the input for a full scale reading. Hence, to measure currents of the order of 10^{-13} to 10^{-12} amperes as was done in this work, an input resistance of the order of 10^{12} ohms was required. Since the capacitance of the outer electrode was about 700 micromicrofarads, the resulting time constant at the input of the electrometer was of the order of 700 seconds.

For the final studies in nitrogen gas a Brown vibrating reed electrometer was used. Its sensitivity permitted the use of an input resistance of 10^{11} ohms; the input time constant was about 70 seconds. The noise and zero drift of the electrometer corresponded to about 1 mv at the input. The measurements for argon gas were made with an Applied

Physics Corp. vibrating reed electrometer, Model 30. Its operation and sensitivity were similar to the Brown instrument. However, the noise was somewhat less, corresponding to about 0.2 mv.

The connections to the outer electrode and the input circuit for the vibrating reed electrometer are shown in Fig. 14. The vibrating reed or modulated capacitor is designated as C_v . To prevent the electrometer from "hunting" it was necessary to install a 600 micromicrofarad damping condenser C_D across the input resistor. Teflon was used as the dielectric material in this condenser to meet the requirements of low polarization and low leakage. When the chamber was operated as a proportional counter, it was necessary to decouple the electrometer from the outer electrode. This was accomplished for radio frequencies by using a Victoreen VX-10 thermal relay to connect a 1 microfarad condenser between the outer electrode and ground. At the same time the input resistor r_g was shunted by closing the switch S_2 .

For both vibrating reed electrometers the quantity which was recorded was the feedback voltage e_f , which was equal to the voltage drop across the input resistor. Thus, the current originating in the ionization chamber was given by

$$i = e_f / r_g$$

where r_g was corrected for leakage through the condenser C_D and the switch S_2 . The leakage through the insulation resistance of the outer electrode was neglected since this resistance was effectively increased by a factor equal to the over-all gain in the electrometer amplifier-feedback loop, approximately 1000.

The calibration of the electrometer consisted essentially of determining the effective input resistance. Three different procedures were used. In the first procedure, the input resistor was removed from the instrument and measured on a Spinlab megohm bridge. This procedure necessarily neglected any leakage in the remainder of the input circuit. In the second method a known current was established by applying a known voltage to a measured resistance connected in series with the input of the electrometer, switch S_1 being open. Since the series resistance was measured on the same Spinlab bridge, this method was not independent of the first. However, it was complementary since it included the effect of any leakage through the damping condenser or other parts of the input circuit.

In the third procedure the capacitance C_s shunting the input resistance was charged to an arbitrary potential and then the rate of discharge was determined by observing the rate of decay of the electrometer feedback voltage e_f . Thus, the shunting capacitance was initially charged to a potential V_0 and allowed to discharge to a potential V at time t .

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FIG.14. SCHEMATIC DIAGRAM OF INPUT CIRCUIT OF VIBRATING REED ELECTROMETER

The value of the input resistance was then computed from the relation

$$V = V_0 e^{-t/(r_g C_s)}$$

whence,

$$r_g = t/(C_s \ln V_0/V) .$$

The capacitance of the damping condenser was measured on a Becco capacitance bridge. This value was combined with the stray capacitance C_0 of the input to obtain the total capacitance shunting the input resistance. Generally the values obtained for r_g by the three procedures agreed within 1 per cent.

H. Center Electrode Voltage Supply

Positive center electrode potentials were supplied by a regulated electronic supply which had an output variable from 1000 to 3000 volts. Further adjustments of this voltage were made by the voltage divider shown in Fig. 15. The negative potentials for the center electrode were supplied from batteries connected to a switching arrangement, also shown in Fig. 15.

V. METHOD OF PROCEDURE

The essential points in the experimental procedure were the adjustment of the chamber pressure, the adjustment of the kevatron beam, and the determination of the three quantities: the energy of the primary ions, the rate at which they entered the chamber, and the ionization produced by them. The techniques of these adjustments and measurements are described in detail below.

A. Chamber Pressure

To change the pressure in the chamber it was necessary to turn off the automatic pressure regulator and manually control the thermal leak power. The chamber pressure was increased by operating the thermal leak at maximum power and adjusting the pressure in the filling system to 20 or 30 psi gauge pressure. Under these conditions the chamber pressure increased at a rate of 20 to 30 mm of oil per hour. The pressure was decreased by turning off the thermal leak power and evacuating the filling system. The valve to the pump-out line was then opened slightly, care being taken not to overload the diffusion pump.

When the chamber pressure reached the desired value, the heater current for the thermal leak was set at 0.5 ampere. The pressure in the filling

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FIG. 15 VOLTAGE SUPPLY FOR CENTER ELECTRODE

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system was then adjusted to about 1 atmosphere. Under these conditions the gas flow was approximately that required to maintain the chamber pressure constant. The automatic regulator was then turned on, adjusted, and switched into operation. A period of 20 to 30 minutes was required for the regulator to stabilize.

B. Kevatron Beam

The energy of the kevatron beam was first estimated by the setting of the high voltage auto-transformer. The desired ion component was located with the magnetic analyzer and the energy of this component was measured with the electrostatic analyzer. The variable auto-transformer in the high voltage fine control circuit was then used to make the final adjustment in the energy while "tracking" the beam with the magnetic and electrostatic analyzers.

The alignment of the beam through the magnetic and electrostatic analyzers was accomplished by adjusting the position of the target end of the accelerator tube to give a maximum current into the ionization chamber for a given set of ion source conditions. Since the ion source was operated with the probe and first electrode at the potential of the case, the ion source pressure and arc voltage were used to adjust the beam intensity.

After the intensity, alignment, and energy of the ion beam had been satisfactorily adjusted, the automatic regulator for the kevatron high voltage was switched into operation and adjusted to the proper operating level.

The current to the entrance slit of the electrostatic analyzer was monitored with the vacuum tube electrometer. The output of this electrometer was recorded with an Esterline-Angus recorder which provided an indication of the stability of the beam current.

C. Energy of Primary Ions

The electrostatic analyzer was relied upon for the determination of the energy of the primary ions. The potential difference between the deflection plates was measured at the beginning and end of each run and the average of the two readings was used to compute the energy of the ions. The difference between the two readings was never greater than 0.1 percent. At each energy the electrostatic analyzer power supply was balanced so that the two deflection plates were at equal and opposite potentials.

D. Counting the Primary Ions

The primary particles entering the chamber were detected and counted by operating the chamber as a proportional counter. The center electrode was operated at a positive potential sufficient to produce 50 volt pulses at the output of the amplifier when its gain was approximately 10^5 . The potential at which the center electrode was operated depended upon the chamber pressure, the energy of the primary ions, and the type of gas. The distribution in pulse heights also varied with the energy and the pressure. The average height and duration of the pulses were measured by observing the pulses on an oscilloscope.

Fig. 16 shows a photograph of pulses for 75 kev protons in nitrogen gas. These pulses were about 8 microseconds long at the base. Fig. 17 shows a photograph of the pulses produced by 75 kev triatomic hydrogen ions in nitrogen. It was not possible to make an ionization yield determination for this ion component due to its breakup in the aperture. This breakup accounted for the three groups of pulses which can be seen in the photograph. The group of largest pulses corresponded to the entrance of all three protons into the chamber, the middle group to two protons, and the group of smallest pulses represented the entrance of only one proton of the triatomic ion. The energy of each proton was approximately one-third of the total energy of the ion.

To determine the proper setting for the discriminator of the scaler, two scalers were operated in parallel. The discriminator of one was kept fixed while the discriminator of the other was varied. Operated in this manner, the ratio of the counting rates of the two scalers was not affected by variations in the beam intensity. When this ratio was plotted as a function of the varied discriminator setting, it showed a plateau as illustrated by Fig. 18. The discriminator was set to operate near the middle of this plateau. The slight slope of the plateau was attributed to the change in the resolving time of counting as the discriminator level was raised.

The resolving time of counting was estimated by observing the pulses on an oscilloscope. Since the hysteresis in the discriminator of the scaler was about 5 volts, the time required for the pulses to rise from zero to a maximum and then fall to five volts below the discriminator level was taken as the resolving time of counting. The resolving times for nitrogen gas were 7 to 10 microseconds and for argon were 15 to 20 microseconds. Counting rates of 1000 to 3000 ct./sec were used for nitrogen and 500 to 2000 ct./sec for argon. In all cases the background count was only a fraction of a count per second and was neglected.

Fig. 16. Proportional counter pulses for 75 kev protons in nitrogen. Pressure, 6 mm Hg; C.E.V., 880 v; 1270 ct./sec.

Fig. 17 Proportional counter pulses for 75 kev triatomic hydrogen ions in nitrogen. Pressure, 6 mm Hg; C.E.V., 880 v; 3570 ct./sec.

E. Ionization Current

The negative ions produced in the chamber were collected on the outer electrode by operating the center electrode at a negative potential. This ionization was measured as a current with a vibrating reed electrometer. The outer electrode was made slightly positive with respect to the chamber walls by inserting a small battery between the input to the electrometer and the outer electrode. In this way the ionization between the outer electrode and the aperture was collected and included in the current measurement.

Since the time constant for the electrometer was about 70 seconds, a period of 400 seconds was allowed for the electrometer to reach a stationary reading. The output of the electrometer was recorded with a Brown "Elektronik" recording potentiometer. The ionization current was read as the last point on the trace before the input was shorted prior to counting.

The zero reading of the electrometer was determined by allowing the electrometer to read for 20 or 30 minutes with no beam in the chamber. The electrodes were operated at the same potentials used for the ionization measurements. Thus, the zero reading included any leakage current or ionization due to cosmic rays or other background radiation. The recorder trace was averaged over this 20 or 30 minute period and used as the zero reading. A zero check was taken at the beginning and end of every run. The results of the two zero checks were averaged and this average was subtracted from the ionization current readings to obtain the true readings.

F. Sequence of Measurements

Fig. 19 shows a block diagram of the measuring apparatus. First, the voltage on the center electrode was adjusted to a negative value which collected all of the ionization but gave no multiplication. The outer electrode was then ungrounded and the electrometer was allowed to record for 400 seconds. The outer electrode was again grounded and the center electrode voltage was adjusted to a positive value which operated the chamber as a proportional counter. The primary ions were counted for 100 seconds.

One serious disadvantage of this technique was that the ionization current and the primary ion rate were not measured simultaneously. Hence, any variation in the incident beam current during the period of counting resulted in an error in the ionization yield determination. To reduce the effect of fluctuations in the primary beam current, the sequence of measurements summarized above was repeated 10 to 25 times and averaged for each ionization yield determination. The histogram shown in

FIG. 18 COUNTING PLATEAU FOR 150 kev PROTONS
IN ARGON

Fig. 20 illustrates the distribution in a set of 50 measurements for 200 kev protons in nitrogen for which σ_s and σ_m represent the sample standard deviation and deviation in the mean, respectively.

VI. ADJUSTMENT OF DATA AND ERROR ANALYSIS

The ionization yield and average energy per ion pair were computed as follows: The difference between the electrometer reading and the electrometer zero was multiplied by the electrometer calibration factor to give the ionization current. The counting rate, the total count divided by time of counting, was corrected for coincidences. The ionization yield per primary particle was then determined by dividing the ionization current by the corrected counting rate. The average energy per ion pair was obtained by dividing the energy of the primary particles by the number of ion pairs produced by each. The uncertainties in the results fall into three categories.

A. Uncertainty in Energy

The error in the energy determinations was dependent upon the absolute calibration and the resolution of the electrostatic analyzer. The resolving power of the instrument was adjusted to approximately 200 for all of the final measurements. This gave rise to an uncertainty in the energy of 0.5 percent. The absolute calibration was based upon the physical dimensions of the analyzer and was estimated to be correct to within 1 percent. Accordingly, the over-all error in the energy measurements was estimated to be 1 percent.

It was necessary to correct the energy for loss in the aperture assembly, and, in the case of nitrogen, for loss in the gap between the aperture and the outer electrode. These energy loss corrections for protons were based upon the energy loss cross sections published by Weyl (61). The length of the aperture was estimated to be 0.01 inch; the pressure in the aperture was assumed to be the average of the pressures at the two sides.* The energy loss corrections for the aperture were of the order of 0.015 kev per mm Hg of chamber pressure.

Since the measurements in nitrogen were made with the outer electrode at the same potential as the chamber walls, it was necessary to correct

*This assumption was somewhat in error because the flow of gas through the aperture was not completely free-molecular flow. It approached viscous flow at the high pressure side and free-molecular flow at the low pressure side (62). Any error in this assumption, however, resulted in only a second-order effect since the energy lost in the aperture was a small fraction of the total energy of the primary ions.

FIG. 19 BLOCK DIAGRAM OF APPARATUS FOR IONIZATION YIELD MEASUREMENTS

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FIG. 20 DISTRIBUTION IN MEASUREMENTS OF IONIZATION YIELD FOR 200 keV PROTONS IN NITROGEN GAS

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for energy loss in the region between the aperture and outer electrode. The length of this gap was estimated to be 0.151 inch. These corrections for protons in the energy range of 25 to 250 kev varied from 2.0 to 2.6 kev for a chamber pressure of 6 mm Hg.

B. Uncertainty in Current Measurements

The calibration of the electrometer relied upon measurements with capacitance and resistance bridges with accuracies of 1 percent. Furthermore, the results of the three methods of calibration discussed in Section IV, G agreed to within 1 percent. Accordingly, the uncertainty in the calibration constant was estimated to be 1 percent.

Additional uncertainties in the current measurements were introduced by the zero drift and the noise of the electrometer. The combined uncertainties due to these two effects varied from 0.2×10^{-14} to 0.5×10^{-14} amperes and were generally less than 0.5 percent of the current reading.

C. Uncertainty in Counting Rates

The greatest errors in counting resulted from variations in the beam intensity; i. e., the beam intensity would change after the current was read and during the period of counting. As discussed in Section V, F, this effect was reduced by repeating the sequence of measurements many times. For each set of readings a sample standard deviation was computed and thereby the statistical uncertainty in the mean was determined. Generally, enough readings were taken so that the deviation in the mean was less than 0.5 percent. Sometimes the beam intensity would drift continuously in one direction in which case a small systematic correction was made in the data.

The resolving time for counting varied over the range of 8 to 20 microseconds depending upon the type of gas and the center electrode potential. The counting rates ranged from 500 to 3000 cts/sec. Consequently, it was necessary to make corrections for coincidences. These corrections were made in accordance with the relation

$$R = R' / (1 - R'T)$$

where R is the true particle rate, R' is the observed counting rate, and T is the resolving time. The corrections for coincidences were largest for argon, ranging from 1 to 5 percent.

Often the beam intensity in the chamber was modulated at 120 cps. This, of course, meant that the instantaneous counting rates were higher than the average, and the number of coincidences was greater than allowed for in the above corrections. An attempt was made to estimate the degree of modulation by observing the pulses on an oscilloscope. This estimate was very crude and the uncertainty in R'T was generally about 25 percent.

Throughout the course of the experiment several different decade scalers were used. It was found that these scalers had slightly different resolving times and sensitivities to noise. In an effort to compensate for these differences, the counting efficiency of each decade scaler was compared with that of the binary scaler which was used throughout the experiment; corrections were made for any differences. These variations in counting efficiency were always less than 0.5 percent. Except for the uncertainties in the absolute calibration factors, the over-all uncertainty in the final results could be reduced by averaging several independent determinations. Generally, the over-all uncertainty in the final values for ionization yield ranged from 1.5 to 2.0 percent.

VII. RESULTS FOR NITROGEN

Most of the preliminary data for nitrogen gas were discarded as being inconsistent and unreliable in absolute value. This was caused by a misalignment of the aperture assembly whereby the protons which entered the chamber had been scattered from the beam stop in front of the aperture. In this scattering process, the protons lost an unknown but significant portion of their energy.

One important observation, which was apparently independent of this misalignment, was the variation of ionization yield with time which elapsed after the initial filling of the chamber. This effect is illustrated by the curve in Fig. 21. In accordance with the above discussion, the data are valid only on a relative basis.

Some preliminary saturation and multiplication studies were made in nitrogen using slowed alpha particles from a U^{235} source. This source, which had an activity of about 4000 disintegrations per second, was placed in the bottom of the outer electrode and covered with a 0.001 inch layer of aluminum foil. Fig. 22 shows a multiplication curve obtained for nitrogen at a pressure of 5.95 mm Hg. The center electrode was operated at potentials of 860 to 890 volts when the chamber was used as a proportional counter. Fig. 23 shows the relative ionization yields of slowed alpha particles for both positive and negative center electrode potentials in the region of saturation.

The results of the final measurements of the ionization yield of protons in nitrogen are presented in Table 2. These measurements were all made at a pressure of 6 mm Hg. The saturation characteristics of the chamber were investigated for a single proton energy, namely, 200 kev. This saturation curve is shown in Fig. 24. The initial energy of the protons is given in the first column of Table 2. The second column

Table 2. Ionization yield data for protons in nitrogen

Proton energy kev	Energy loss kev	Center electrode potential volts (-)	Y- coul. per proton $\times 10^{16}$	W ev/ip	Error percent	Y _c coul. per proton $\times 10^{16}$	W _c ev/ip
23	2.20	409	1.016	36.3	3.9	1.116	33.0
36	2.39	45	1.494	38.6	2.7	1.597	36.1
50	2.60	409	2.137	37.5	3.0	2.249	35.6
75	2.67	409	3.270	36.7	1.8	3.387	35.5
100	2.57	409	4.378	36.6	1.8	4.491	35.7
150	2.30	409	6.59	36.5	1.9	6.69	35.9
200	2.02	325	8.70	36.8	1.7	8.79	36.5
250	1.83	409	10.85	36.9	1.8	10.93	36.7

shows the energy lost by the protons in the aperture and the gap between the aperture and outer electrode. The potential at which the center electrode was operated during the current measurements is found in column three. The ionization yield Y and the average energy per ion pair W are given in columns four and five, respectively, for which no corrections have been made for energy loss in the aperture assembly. Column six shows the estimated uncertainties for these results due to errors in the measured quantities. The values for ionization yield and average energy per ion pair shown in columns seven and eight, respectively, have been corrected for the corresponding energy losses given in column two. The uncorrected values of ionization yield in column four have been plotted in Fig. 25. The straight line represents a least squares plot of the points at 75, 100, 150, and 200 kev. The slope of this line corresponds to 36.6 ev per ion pair; it intercepts the energy axis at 0.10 kev.

FIG. 21 VARIATION OF IONIZATION YIELD WITH TIME
ELAPSED AFTER FILLING CHAMBER

FIG. 22 MULTIPLICATION CURVE FOR SLOWED ALPHA PARTICLES IN NITROGEN

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FIG. 23 SATURATION CURVES FOR SLOWED ALPHA PARTICLES IN NITROGEN

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FIG. 24 SATURATION CURVE FOR 200 kev PROTONS IN NITROGEN

50

FIG. 25 IONIZATION YIELD OF PROTONS IN NITROGEN

VIII. DISCUSSION OF THE RESULTS FOR NITROGEN

In regard to the results for nitrogen gas it should be kept in mind that this study was very preliminary and far from complete. The primary purpose of this preliminary investigation was to check the feasibility of the experimental method and to check the performance of the apparatus. Nitrogen was used so that gas purity would not be too important.

No attempt was made to purify the gas or to check its purity. However, the variation of the ionization yield with time, as illustrated in Fig. 21, demonstrates that the gas was far from pure. The slow increase in ionization yield with time is indicative of a leak in the chamber and is consistent with an increase in the percentage of oxygen in the gas. A comparison of the relative increase with the ionization yield of alpha particles in various mixtures of nitrogen and oxygen (16) indicated that the equilibrium gas mixture contained approximately 10 percent oxygen. Since the measurements for the data plotted in Fig. 21 were made before the aperture assembly was properly aligned, the absolute values have little significance. After the final measurements in nitrogen were completed, the chamber was tested for vacuum tightness and at least two leaks were located. Consequently, it can be assumed that the results given for nitrogen are actually for a gas mixture with a composition somewhere between pure nitrogen and air.

It should be noted that the results of the investigation with slowed alpha particles are for an ionization distribution which is radically different from that for a proton beam. Consequently, it is possible that any conclusions in regard to saturation and multiplication may not be valid for a proton beam. There are, however, several observations worthy of note. From the multiplication curve in Fig. 22 it can be seen that the multiplication factor for proportional counter operation was about 10. There are two noteworthy points illustrated in Fig. 23. The first is the difference in the shape of the saturation curves for negative and positive center electrode potentials. For negative potentials the curve rises more slowly at the beginning but the saturation region extends over a greater voltage range. This latter difference occurs because relatively few of the electrons produced in the ionization processes enter the high field region around the center electrode in the case of negative potentials. Multiplication and breakdown are finally brought about by secondary emission produced by positive ion bombardment of the center electrode. The difference in the rising parts at the beginning of the saturation curves was probably caused by space charge effects. Space charge effects in cylindrical ionization chambers have been discussed by Lapsley (63) and his conclusions seem to confirm the above observations.

The second point of interest in Fig. 23 is the difference in the saturation values of ionization current for positive and negative potentials. This difference was also noted for a proton beam. No completely satisfactory explanation has been given for this phenomenon. A similar asymmetry has been discussed by Greening (64) on the basis of the emission of electrons from the surfaces of the electrodes. However, his arguments lead to an effect which has a polarity opposite to that observed in Fig. 23. The experimental data for cylindrical ionization chambers discussed by Lapsley (63) showed an asymmetry similar to that observed in the present experiment. He offered no explanation for this asymmetry, but it appears that space charge effects might account for it.

The incompleteness of the final studies of the ionization yield of protons in nitrogen left several significant uncertainties in the results. First, saturation was investigated at only one energy. The difference in the value obtained for the average energy per ion pair at energies of 23 kev and 36 kev indicated that there may have been some multiplication around the end of the center electrode. A small percentage of multiplication in this region would not seriously affect the results for 200 kev protons. For energies below 50 kev, this multiplication would directly affect the results because most of the ionization would be produced near the end of the center electrode. Secondly, there was some question as to what correction should be made for the ionization lost in the gap between the aperture and outer electrode. It was probable that some of this ionization was collected by the field which extended through the hole in the outer electrode. Furthermore, there would have been a natural diffusion of ions to the outer electrodes from this region. Undoubtedly, some correction is necessary for the data plotted in Fig. 25. The final results should fall somewhere between the uncorrected and fully corrected values given in Table 2.

Subsequent studies in argon have indicated that a pressure of 6 mm Hg was not sufficient to stop the higher energy protons. Protons with energies above 150 kev were probably losing part of their energy to the electrodes of the chamber and the values of ionization yields for these energies may be too low. Only the four points between 75 and 200 kev were used in the least squares plot of the data because of the large uncertainties for energies outside of this range. At lower energies the loss in the aperture assembly became an appreciable part of the total energy and at higher energies the loss to the electrodes may have been appreciable. The slope of the least squares plot and the corresponding value of W' should be relied upon only as an order of magnitude since the systematic effects which were present were probably greater than the random uncertainties specified for these quantities. Even so, there is relatively good agreement between the value of W' obtained in the present experiment and the value of W commonly reported for alpha particles in nitrogen, namely, 36.3 ev/ip (11,16,19). It is also of interest to note the smallness of the differ-

ences between this value of W and those reported by Jentschke (32) and Gerthsen (33) for protons in air, namely 35.9 and 36 ev/ip, respectively. From this comparison it appears that the air contamination in the gas did not seriously affect the results of the present measurements. The value given for E_0 in Fig. 25 is of little significance because of the large uncertainties in the data.

IX. RESULTS FOR ARGON

A more precise study was made of the ionization yield of protons in argon. The characteristics of the chamber were studied in detail in an effort to account for the many variations observed in the data. First it was necessary to ascertain that all of the ionization produced in the chamber was collected. This was done by measuring the ionization yield as a function of the center electrode potential. These saturation studies were made for 50 and 200 kev protons. Some of the saturation curves obtained are displayed in Figs. 26, 27, 28, and 29. It should be noted that the average energy per ion pair has been plotted rather than the usual ionization yield. This was done as a means of normalizing the data which was necessary because the energy varied slightly for each determination.

The collection of the ionization in the gap between the aperture and outer electrode was also investigated. This study was made at low energies because the total ionization became more sensitive to the ionization produced in this gap. The ionization yield of 50 kev protons was measured for several different values of outer electrode potential. The results for three different pressures are shown in Table 3. The values of ionization yield per proton are given in column four. The last column shows the corresponding values of average energy per ion pair for which the uncertainties do not include the estimated errors in the absolute calibration factors for the electrostatic analyzer and electrometer.

It was also necessary to establish that no primary ions were lost to the electrodes. This was accomplished by measuring the ionization yield as a function of the pressure. The results of these investigations were illustrated by the curves in Fig. 30.

The final values for the ionization yield of protons in argon were generally the average of several determinations. Since the accuracy of the determinations varied considerably, the values used in obtaining the averages were weighted accordingly. In choosing the final values, careful consideration was given to the results of the saturation and pressure studies. The final results for the ionization yield of protons in argon are given in Table 4. For each energy studied both the ionization yield

Table 3. Ionization yield of 50 kev protons for various outer electrode potentials

Chamber pressure mm Hg	Outer electrode potential volts (+)	Center electrode potential volts (-)	Y coul. per proton $\times 10^{16}$	W ev/ip
4.46	0	137	2.784	$28.77 \pm .37$
4.46	1.5	137	2.869	$27.92 \pm .28$
4.46	3.0	137	2.869	$27.92 \pm .36$
6.50	0	137	2.724	$29.41 \pm .39$
6.50	1.5	137	2.922	$27.41 \pm .29$
6.50	3.0	223	2.924	$27.39 \pm .37$
8.79	1.5	223	2.865	$27.96 \pm .26$
8.79	3.0	223	2.876	$27.85 \pm .30$
8.79	4.5	223	28.92	$27.70 \pm .27$

and average energy per ion pair are given. The ionization yields are plotted in Fig. 31. The straight line represents a weighted least squares plot of the data and has a slope corresponding to 26.5 ± 0.5 ev/ip. The least squares plot intercepts the energy axis at 1.4 ± 0.9 kev indicating a slight ionization defect for protons.

Table 4. Ionization yield of protons in argon

Proton energy kev	Ionization yield coul./proton x 10 ¹⁶	Average energy per ion pair ev
25	1.455 ± .026	27.52 ± .49
50	2.879 ± .044	27.82 ± .43
100	5.957 ± .114	26.89 ± .51
150	8.923 ± .145	26.93 ± .44
200	12.04 ± .18	26.61 ± .40
250	15.26 ± .25	26.25 ± .43

X. DISCUSSION OF RESULTS FOR ARGON

Although no careful test was made of the gas purity, there was no evidence of significant contamination. The chamber was filled with tank argon supplied by the Matheson Company and was reported to have a purity of 99.99 percent. The chamber was filled through the hot calcium purifier as described in Section IV, D, 4. The rise times of the proportional counter pulses were much longer for argon than for nitrogen. An appreciable nitrogen or carbon dioxide contamination would have noticeably decreased these rise times. However, upon filling the chamber with new gas there was no detectable change in the rise time of the pulses, the multiplication, or ionization yield. On the basis of these observations it was concluded that the gas purity was at least 99.0 percent.

The cylindrical geometry and highly nonuniform electrical fields in the chamber made it difficult to attain saturation. The degree of difficulty depended upon the spatial distribution of the ionization. This distribution varied with the energy of the protons and the pressure in the chamber. The spatial distribution of the ionization produced in a gas by a collimated beam of heavy ions has been studied by Evans, Stier, and Barnett (65) and by Cook, Jones, and Jorgensen (66). The results of the former investigation indicated the attenuation of the beam of ions was

FIG. 26 SATURATION CURVES FOR 50 kev PROTONS
IN ARGON

FIG. 27 SATURATION CURVES FOR 50 kev PROTONS
IN ARGON

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FIG. 28. SATURATION CURVE FOR 200 kev PROTONS
IN ARGON.

FIG. 29 SATURATION CURVES FOR 200 kev PROTONS
IN ARGON

FIG. 30 AVERAGE ENERGY PER ION PAIR FOR 50 AND 200 kev PROTONS AS A FUNCTION OF CHAMBER PRESSURE

FIG.31 IONIZATION YIELD OF PROTONS IN ARGON

approximately exponential in the axial direction and approximately Gaussian in the lateral direction. The over-all distribution of ionization in space was represented by an empirical formula of the type

$$C \approx e^{-(AR + Br^2/R^2)}$$

where C is the ionization density; A and B are constants; R and r are the axial and lateral distances of a given point from the point of entry of the beam. The lateral spread of the ionization increases with energy causing a greater portion of the ionization to be produced near the outer electrode. In this extended region the fields are weak and, consequently, the region is difficult to saturate. Thus, in the present experiment it was more difficult to saturate the chamber for 200 kev protons than for 50 kev. The experimental saturation curves seem to confirm these conclusions. The curve in Fig. 27B for 50 kev protons presents strong evidence of saturation to within 1 percent. The saturation curves for 200 kev protons are less definite although this is partially because fewer points were plotted. Even so, at a pressure of 8.96 mm Hg at which the final measurements were made, the chamber was assumed to be saturated to within 1 percent on the basis of the curve in Fig. 29B.

The data in Table 3 indicated that an outer electrode potential of 1.5 to 3.0 volts was adequate to collect all of the ionization produced in the gap between the aperture and outer electrode. It was assumed, therefore, that the correction for loss in the aperture itself was the only one necessary for the energy of the protons. This correction was at most only 0.13 kev and so was not important.

Undoubtedly, some of the primary ions were lost to the center electrode and at sufficiently low pressures some were lost to the outer electrode. This loss to the electrodes decreased as the pressure was increased which accounted for the negative slope of the pressure curve in Fig. 30B. Even at the maximum pressure there was still possibly significant loss to the electrodes. To estimate this loss it was necessary to know the scattering of the primary ions. Multiple scattering was involved which is difficult to calculate. However, to estimate the scattering of the primary ions it was possible to use the ionization density contours for protons in argon published by Cook, et al. (66). Using these data and the above empirical equation for the ionization distribution, an approximate calculation was made of the energy lost to the center electrode by 250 kev protons in argon at a pressure of 9 mm Hg. The results established 0.8 percent of the total energy of the ion beam as an upper limit for the energy lost. The energy loss was less at lower energies.

The pressure curve of Fig. 30A seems to indicate the presence of a second effect. The variations were not outside of the uncertainties of the data but were, in general, reproducible to some degree. The rise in W at low pressure was probably caused by loss of protons to the electrode as

discussed above. However, the increase of W at higher pressure was not readily explained. It will be necessary to improve the accuracy of the measurements before the existence of this effect can be definitely confirmed.

It may be possible to attribute the above pressure anomaly to emission of electrons from the electrodes. Generally, it is expected that the emission from the center electrode of a cylindrical ionization chamber will be less than from the outer electrode because of difference in area. However, in the present experiment, the density of excited and ionized atoms was much greater in the vicinity of the center electrode. As the pressure was decreased, the lateral dimension of the ionization envelope expanded and surrounded the center electrode with a greater density of excited and ionized atoms. This could have increased the emission of secondary electrons. Since the center electrode was operated at a negative potential, this increase in secondary emission would have been detected as an increase in the ionization yield. Undoubtedly, secondary emission from the electrodes existed, but whether it was significant remains to be determined. This effect might account for some of the differences in measurements of ionization yields by fast (electron collection) and by slow (total ion collection) chambers.

Since the velocity of a 200 kev is about the same as that of an 800 kev alpha particle, it is to be expected that the average energy per ion pair for the proton should be about the same as for the alpha particle. Investigations (14,11) of the ionization yield of alpha particles in argon for energies above 1 Mev have indicated the existence of a straight line relation between the ionization yield and the energy. The slope of this linear function corresponded to 26.4 ev/ip. The present data for protons in argon seem to fit a straight line and the value obtained for W , 26.5 ev/ip, is in good agreement with the above results for alpha particles. The value of 1.38 kev for E_0 is consistent with Jesse's (14) prediction that the ionization defect, if present, should be small.

It can be seen in Table 4 that the average energy per ion pair increases as the energy decreases. This variation can be interpreted as indicating that the energy loss processes competing with ionization are becoming more significant.

XI. CONCLUSIONS

The ionization yield of protons in nitrogen was measured primarily as a preliminary check of the feasibility of the experimental method and to test the performance of the apparatus. The results of these measurements were subject to large uncertainties and can be relied upon only as an order of magnitude. Despite the large uncertainties, the values obtained for the average energy per ion pair are consistent with those reported for alpha particles in nitrogen.

The measurements of the ionization yield of protons in argon were more carefully done and the results can probably be relied upon within the uncertainties stated. The relation between ionization and energy seemed to fit a straight line and the slope of the line is in good agreement with high energy alpha data. The ionization defect for protons in argon is probably less than 2 kev.

Although the characteristics of the ionization chamber were investigated in considerable detail, there remain several phenomena which need further study. The asymmetry in the saturation current for positive and negative center electrode potentials needs to be more carefully studied and explained. The variation of ionization yield with pressure remains to be verified and also explained. More accurate measurements for saturation curves are needed. In general, all of these phenomena require more accurate data. To accomplish this, greater accuracy in the calibration of the electrostatic analyzer and electrometer will be necessary and, above all, some way is needed to lessen or eliminate the effect of instabilities in the primary ion beam.

Over all, it is felt that the experimental method has proven to be relatively successful and perhaps adequate to continue with an investigation of more interesting combinations of ions and gases. Some measurements which are particularly of interest at very low energies are: protons in hydrogen, protons in helium, and helium ions in helium. It is these simpler ions and gases for which theoretical calculations are being made (5,6,7,8). Additional measurements which are of considerable interest are those which involve very heavy ions: argon ions in helium and argon ions in argon. From these latter studies it may be possible to determine the significance of the secondary ionization produced by recoil gas atoms. For completeness and to satisfy the demands for this fundamental information, all the combinations of ions and gases originally proposed should be investigated.

LITERATURE CITED

1. H. A. Bethe and J. Ashkin. In E. Segre, ed. Experimental Nuclear Physics. Vol. 1. N. Y. John Wiley and Sons, Inc. p. 166. 1953.
2. S. K. Allison and S. D. Warshaw, Revs. Mod. Phys. 25, 779 (1953).
3. N. Bohr, Kgl. Danske Videnskab. Selskab. Mat.-fys. Medd. 18, nr. 8 (1948).
4. H. A. Bethe, Ann. Physik 5, 325 (1930).
5. D. R. Bates and G. W. Griffing, Proc. Phys. Soc. (London) A66, 961 (1955).
6. D. R. Bates and G. W. Griffing, Proc. Phys. Soc. (London) A67, 663 (1954).
7. D. R. Bates and G. W. Griffing, Proc. Phys. Soc. (London) A68, 90 (1955).
8. B. L. Moiseiwitsch and A. L. Stewart, Proc. Phys. Soc. (London) A67, 1069 (1954).
9. J. K. Knipp and R. C. Ling, Phys. Rev. 82, 30 (1951).
10. W. P. Jesse and J. Sadauskis, Phys. Rev. 88, 417 (1952).
11. W. P. Jesse and J. Sadauskis, Phys. Rev. 90, 1120 (1953).
12. H. S. W. Massey and E. H. S. Burhop, Electronic and Ionic Impact Phenomena. London: Oxford University Press. 1952.
13. L. H. Gray, Proc. Camb. Phil. Soc. 40, 72 (1944).
14. W. P. Jesse, H. Forstat, and J. Sadauskis, Phys. Rev. 77, 782 (1950).
15. G. Stetter, Zeits. f. Physik 120, 639 (1943).
16. T. E. Bortner and G. S. Hurst, Phys. Rev. 93, 1236 (1954).
17. J. Sharpe, Proc. Phys. Soc. (London) A65, 859 (1952).
18. J. M. Valentine and S. C. Curran, Phil. Mag. 43, 964 (1952).

19. W. Haeberli, P. Huber, and E. Baldinger, *Helv. Phys. Acta* 25, 467 (1952).
20. G. Bertolini, M. Bettoni, and A. Bisi, *Nuovo Cimento* 9 (Ser. 9), 1004 (1952).
21. L. O. Herwig and G. H. Miller, *Phys. Rev.* 94, 1183 (1954).
22. G. Bertolini, M. Bettoni, and A. Bisi, *Phys. Rev.* 92, 1586 (1953).
23. C. E. Melton, G. S. Hurst, and T. E. Bortner, *Phys. Rev.* 96, 643 (1954).
24. D. W. Curtis, Unpublished Ph. D. Thesis, Ames, Iowa, Iowa State College Library. (1955).
25. G. C. Hanna, *Phys. Rev.* 80, 530 (1950).
26. J. Rhodes, W. Franzen, and W. E. Stephens, *Phys. Rev.* 87, 141 (1952).
27. U. Facchini, E. Gatti, and E. Germagnoli, *Nuovo Cimento* 8 (Ser. 9) 145 (1951).
28. W. Franzen, J. Halpern, and W. E. Stephens, *Phys. Rev.* 77, 641 (1950).
29. R. B. Leachman, *Phys. Rev.* 83, 17 (1951).
30. L. O. Herwig and G. H. Miller, *Phys. Rev.* 95, 413 (1954).
31. H. W. Schmitt, U. S. Atomic Energy Commission Report No. AECD-3628 (1953).
32. W. Jentschke, *Phys. Z.* 41, 524 (1940).
33. C. Gerthsen, *Ann. Phys. (Leipzig)* 5, 657 (1930).
34. G. Stetter and W. Jentschke, *Zeits. f. Physik* 110, 214 (1938).
35. P. R. Tunncliffe and A. G. Ward, *Proc. Phys. Soc. (London)* A65, 233 (1952).
36. A. Rostagni, *Nuovo Cimento* 13 (Ser. 8), 391 (1936).
37. H. W. Berry, *Phys. Rev.* 62, 378 (1942).

38. P. Rudnick, Phys. Rev. 38, 1342 (1931).
39. J. P. Keene, Phil. Mag. 40, 369 (1949).
40. H. F. Batho, Phys. Rev. 42, 753 (1932).
41. F. Wolf, Ann. der Physik 23, 627 (1935).
42. D. H. Wilkinson. Ionization Chambers and Counters. London. Cambridge University Press. 1950.
43. B. B. Rossi and H. H. Staub. Ionization Chambers and Counters. N. Y. McGraw-Hill Book Company, Inc. 1949.
44. D. R. Corson and R. R. Wilson, Rev. Sci. Instr. 19, 207 (1948).
45. F. L. Ribe, Phys. Rev. 83, 1217 (1951).
46. H. Kanner, Phys. Rev. 84, 1211 (1951).
47. E. Snitzer, Phys. Rev. 89, 1237 (1953).
48. P. M. Stier, C. F. Barnett, and G. E. Evans, Phys. Rev. 96, 973 (1954).
49. W. C. Elmore and M. Sands. Electronics. N. Y. McGraw-Hill Book Company, Inc. 1949.
50. G. H. Miller, R. A. Lowry, and J. E. Osher, U. S. Atomic Energy Commission Report No. ISC-319 (1953).
51. W. Walcher, Nucleonics 5, 42 (1949).
52. J. A. Phipps. Unpublished M. S. Thesis. Ames, Iowa, Iowa State College Library. (1955).
53. C. J. Cook, E. Jones, and T. Jorgensen, Phys. Rev. 91, 1417 (1953).
54. G. H. Miller, Rev. Sci. Instr. 24, 549 (1953).
55. A. M. Billings and C. A. Mossman, U. S. Atomic Energy Commission Report No. ORNL-1492, p. 29 (1953).
56. R. A. Lowry, J. E. Osher, and G. H. Miller, U. S. Atomic Energy Commission Report No. ISC-599 (to be published).

57. W. R. Smythe. Static and Dynamic Electricity. N. Y. McGraw-Hill Book Company, Inc. p. 76. 1950.
58. K. Enslein and B. Brainerd, Rev. Sci. Instr. 24, 916 (1953).
59. R. L. Chase, Rev. Sci. Instr. 25, 1219 (1954).
60. W. A. Rhinehart. Ames, Iowa. Electronic Shop, Institute for Atomic Research, Iowa State College. Unpublished Research. 1952.
61. P. K. Weyl, Phys. Rev. 91, 289 (1953).
62. S. Dushman. Vacuum Technique. N. Y. John Wiley & Sons, Inc. p. 84. 1949.
63. A. C. Lapsley, Rev. Sci. Instr. 24, 602 (1953).
64. J. R. Greening, Brit. J. Radiol. 27, 163 (1954).
65. G. E. Evans, P. M. Stier, and C. F. Barnett, Phys. Rev. 90, 825 (1953).
66. C. J. Cook, E. Jones, and T. Jorgensen, U. S. Atomic Energy Commission Report No. AECU-2467 (1952).

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