1953

Ionization yields of fission fragments in gases

Lloyd Otto Herwig

Iowa State College

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UMI®
IONIZATION YIELDS OF
FISSION FRAGMENTS IN GASES

by

Lloyd Otto Herwig

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Physics

Approved:

Signature was redacted for privacy.

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1953
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NOMENCLATURE

\( v \) - Velocity of a particle
\( v_0 \) - Bohr velocity \( = \frac{e^2}{\hbar} \)
\( E \) - Initial energy of an incident particle
\( E_\alpha \) - Initial energy of an alpha particle
\( E_f \) - Initial energy of a fission fragment
\( I \) - Ionization (total number of ion pairs)
\( W \) - Average energy per ion pair
\( W^* \) - Rate of energy loss of a particle \( \frac{dE}{dI} \)
\( W' \) - Asymptotic value of \( W \) and \( W^* \)
\( \alpha \) - Alpha particle
\( f \) - Fission fragment
\( \Delta \) - Ionization defect for a particle
\( \Delta' \) - Maximum ionization defect
\( \gamma \) - Alpha recoil nucleus
\( lf \) - Light fission fragment
\( hf \) - Heavy fission fragment
\( R \) - Ratio of fission fragment to alpha particle ionization
\( U \) - Uranium
\( X \) - Electric field
\( X_{gc} \) - Electric field in the grid-collector region
\( X_{gs} \) - Electric field in the grid-source region
NOMENCLATURE (continued)

- $Z$ - Ratio of electric fields, $X_{gc} / X_{gs}$
- $Z_m$ - Observed minimum ratio of fields
- $\eta$ - Electron temperature in a gas
- $\xi$ - Distance between adjacent grid wires
- $\sigma$ - Shielding inefficiency of the grid
- $d$ - Diameter of the grid wires
- $d_{gc}$ - Distance between the grid and collector electrodes
- $d_{gs}$ - Distance between the grid and source electrodes
- $v_{gc}$ - Drift velocity in the grid-collector field, $E_{gc}$
- $v_{gs}$ - Drift velocity in the grid-source field, $E_{gs}$
- $l$ - Projection along the electric field of a particle path length
- $P$ - Pressure of a gas in millimeters of mercury
- $V_{gc}$ - Voltage between the grid and collector electrodes
- $V_{gs}$ - Voltage between the grid and source electrodes
- $A, a$ - Argon gas
- $He$ - Helium gas
- $N$ - Nitrogen gas
- $Ne$ - Neon gas
- $Kr$ - Krypton gas
- $CO_2$ - Carbon dioxide gas
- $D$ - Diffusion coefficient
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INTRODUCTION

Discussion and Literature Survey

The scattering and stopping of energetic atomic particles in passing through matter and the resultant ionization and radiation effects have provided some of the most important sources of information regarding the constitution of nuclei. Until 1939 the sources of energetic particles were limited to light nuclei which were obtained from radioactive bodies, from particle accelerators, and from nuclear transmutations. The discovery of the fission process, in which a heavy nucleus splits into two fragments, made available a group of relatively heavy particles with energies up to approximately 100 Mev. Thus it has been possible to study the penetration through matter of high energy particles having masses and charges many times larger than those previously available. It was shown that certain characteristics which were of minor consequence for light particles in the scattering and stopping of energetic atomic particles were accentuated by these properties of the fission fragments. Niels Bohr \(^1\) published a

\[\text{\footnotesize \cite{Bohr1948}}\]

comprehensive theoretical discussion of the phenomena of the penetration of atomic particles, including the fission fragments, through matter, and surveyed the experimental contributions up to that time. The term, ionization defect, was introduced by Knipp et al. in a theoretical study which attempted to describe the phenomena associated with the stopping of heavy charged particles in a gas, and by Hanna in an experimental paper on the energy-ionization relation for alpha particles. To form the basis for an understanding of the present experiment some of the ideas which were summarized in these publications have been used. It has been assumed in this discussion that the incident particle is passing through gaseous matter.

A heavy charged particle in its passage through a gas loses its energy by means of electronic and atomic collisions. In the electronic, or inelastic, collisions energy is transferred to individual electrons of the gas atoms to produce excitation and ionization. In the atomic, or elastic, collisions momentum and kinetic energy are

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transferred to the transitory motion of the stopping atoms. Further, the secondary electrons, which are stripped from the gas atoms, and the recoil gas atoms have electronic and atomic collisions with other atoms.

Bohr developed a criterion for determining whether electronic or atomic collisions predominate along the range of a particle being stopped in matter. The criterion is based on the velocity of an electron which is in the lowest level of the Bohr model of the hydrogen atom ($v_0 = \frac{e^2/\hbar}{2} \approx 2.2 \times 10^8$ cm/sec). For an incident particle velocity much greater or much less than $v_0$, electronic or atomic collisions, respectively, predominate along the path. When the velocity of the particle is much less than $v_0$, the cross section for capture of electrons is much larger than that for loss, and the charge of the incident particle is essentially zero. Thus, in this low velocity region electronic collisions are unimportant and atomic collisions predominate.

According to the ideas developed theoretically by Bohr, the energy transferred by an incident particle which is in the velocity range where atomic collisions predominate gives rise, in general, to recoil velocities which are less than $v_0$. The recoiling gas atoms undergo atomic collisions with other gas atoms, and a large
fraction of the energy transferred in this manner goes directly (that is, without appreciable intermediate excitation and ionization) into thermal motion of the gas atoms. The initial energy and the mass of the incident particle largely determine the importance of atomic collisions in the stopping processes. Knipp et al. recently demonstrated that the energy loss of a slow heavy particle is due predominately to recoil atoms; and, therefore, ionization by secondary heavy particles contributes a large fraction of the total ionization. When the secondary particle ionization efficiency is low, the average ionization efficiency for the incident particle is greatly reduced. Thus the average energy loss per ion pair over the range of the incident particle effectively increases with an increase in the number of recoil atoms which have a reduced ionization efficiency.

For an incident particle which is completely stopped in a gas, the average energy per ion pair, \( W \), is obtained from the relation \( E / I \), where \( E \) is the initial energy of the particle and \( I \) is the total number of ion pairs produced. The instantaneous value of the energy per ion pair at a particular point in the range of the particle is given by the differential expression
\[ W^* = \frac{dE}{dI}. \]

Gray \(^4\), Bethe \(^5\), and Wilkinson \(^6\) reviewed some of the experimental data concerning the value of \( W \) as a function of the type of incident particle, of the energy of the incident particle, and of the stopping gas. For fast particles \((v > v_0)\) with fixed charge, \( W \) and \( W^* \) tend to approach a value \( W' \) which is largely independent of the mass, charge, and velocity of the ionizing particle but does depend on the nature of the stopping gas. For air there is evidence of a relatively large dependence of \( W \) on the initial energy for electrons below 10 Kev, protons below 2.5 Mev, and alpha particles below 4 Mev. The value of \( W \) for the rare gases and hydrogen appears to be more nearly constant than for other gases. Fano \(^7\) gave arguments indicating why \( W \) for all gases was of the same order of magnitude and was not correlated with the ionization potential of the gas. However, recent experiments using very pure gases showed that the value of \( W \) for helium and neon was up to

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\(^7\) U. Fano, Phys. Rev. \(70\), 14 (1946).
40 percent higher than that previously measured. These later values of $W$ for the rare gases correlate well with the ionization potentials. Of the rare gases, argon has been the one most used by experimentalists investigating the dependence of $W$ on the initial energy of a particle. The notations, $x_y W$, $x_y W^*$, and $x_y W'$ etc. are used in the following discussion to represent $W$, $W^*$, $W'$ etc., respectively, in a particular gas $x$ and for a particular particle $y$. The chemical symbols have been used to represent the various gases, and the alpha particle and the fission fragment have been represented by $\alpha$ and $f$, respectively.

If an ionizing particle is allowed to spend all of its range in an ionization chamber, then the resulting electrical pulse can be made accurately proportional to the number of ion pairs formed. Further, if $W^*$ remains constant over the entire track length of the particle, the electrical pulse can be taken as a measure of the initial energy, $E = \frac{I}{W^*}$. Cranshaw and Harvey \(^8\) and Jesse et al. \(^9\) using natural alpha particle

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emitters confirmed the constancy, within experimental error, of $\alpha W^*$ for initial energies greater than 4 Mev. However, there is disagreement between them over the value of $\alpha W^*$ at low energies. Cranshaw and Harvey, using electron collection, found that $\alpha W^*$ increased at the low energies, and Jesse et al., using positive ion collection, found that $\alpha W^*$ remained constant within experimental error down to zero energy. Rhodes et al. and Hanna working with low energy alpha particles from nuclear reactions and using electron collection obtained results which support the increase of $\alpha W^*$ at low energies. It is probable that the discrepancy mentioned above will be resolved by a more complete understanding of the differences between fast and slow ionization chambers and of the differences in gas purity.

For an incident particle the energy which does not show up as ionization at the high energy rate $W'$ (or the extra energy which is lost directly to thermal motion when $W^*$ is greater than $W'$) can be treated in terms of the ionization defect, $\Delta = E - I W'$. The ionization defect is a slowly varying function which ranges in value from the initial energy of the incident particle to a maximum energy.

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value, which depends on the characteristics of the incident particle. If the incident particle has less than a certain minimum energy, it produces no ionization but expends its energy in elastic collisions, so that $I = 0$ and $\Delta = E$. At higher energies $W^*$ approaches asymptotically a constant value, within experimental error, and $\Delta$ approaches asymptotically a maximum value $\Delta'$. If particles having a wide range of initial energies were available for study, such as various alpha particles, an $E$ vs $I$ curve could be plotted. Those incident particle energies which were large enough to approach a constant ionization defect would fall close to a straight line on the $E$ vs $I$ curve; that is, the differences in ionization would be closely proportional to the differences in energy. If the straight line through a series of points which would have a constant $\Delta$ were extrapolated to zero on the $E$ vs $I$ plot, it would intercept the energy axis close to $\Delta'$, and the slope of this straight line would be close to $W'$.

Fig. 1 illustrates pictorially for alpha particles some of the terms which have been defined in the previous discussion. The $E_{\alpha}$ vs $I_{\alpha}$ data of Cranshaw and Harvey \textsuperscript{8} for alpha particles in argon gas has been indicated on Fig. 1a by crosses. Six groups
FIG. 1a

FIG. 1b

FIG. 1 PICTORIAL DIAGRAM FOR ALPHA PARTICLES
of alpha particles of which the energies in the range from 5 to 9 Mev were known from magnetic deflection experiments were used, and the points on the $E_\alpha$ vs $I_\alpha$ diagram fell on a straight line within 1/10 percent. When the dashed line through the points was extrapolated to zero ionization, the intercept on the $E$ axis gave $\Delta E_\alpha = 85 \pm 10$ Kev. Fig. 1b is an expanded view of Fig. 1a near the origin. Since a particle of zero energy produces zero ionization, the $E_\alpha$ vs $I_\alpha$ curve at low energies passes through the origin, as suggested by the dotted lines. The value of $\alpha W_\alpha$ is given by the slope of the curve at the energy which corresponds to that of the particle. For a given $E_\alpha$ the slope of a line from the origin to the curve gives the value of $\alpha W_\alpha$. By drawing a line through the origin with a slope of $\alpha W'$, the energy coordinate of a point on the curve is divided into two parts, $\Delta E_\alpha$ and $I_\alpha \alpha W'$ (or $(I_\alpha W')_a$).

When an alpha particle with initial energy of 5 Mev is stopped in a gas, it loses that energy predominantly through electronic collisions because its velocity is much greater than $v_\alpha$ during most of its range. An energy of approximately 100 Kev is associated with an alpha particle of residual velocity $v_\alpha$. Those alpha
particles with initial energy in the hundreds of kilovolts region lose a larger percentage of their initial energy through atomic collisions, as indicated in Fig. 1b. However, Fig. 1a indicates that a 5 MeV alpha particle loses less than 2 percent of its initial energy through atomic collision processes, and even if the recoiling atoms have a reduced ionization efficiency, the total ionization yield is largely unaffected. Experimental evidence for natural alpha particles stopped in argon gas has indicated that $\Delta_\alpha$ is less than 2 percent. No reliable experimental data are available at this time concerning the $E$ vs $I$ curves for alpha particles in light gases, such as helium and hydrogen. For alpha particles of initial energy greater than 4 Mev it does not seem unreasonable to assume that the $\Delta_\alpha$ for all gases is no larger than approximately 2 percent of the initial energy.

Few $E$ vs $I$ data are available for any type of particle having velocities of the order of magnitude $v_0$ and lower. Madsen $^{11}$ measured in argon gas the ionization produced by recoil nuclei from alpha decay of Po, Th C, and Th C'. These nuclei have energies in the range from 100 to 170 Kev ($\approx 4 \times 10^{-7}$ cm/sec).

and large masses which differ by a few atomic mass units. Thus the graph of $E$ vs $I$ for the three recoil particles was plotted with small error on the same curve. The slope of a straight line drawn through the three points gave a value of $\frac{a}{\eta}$ which was more than twice the value of $\frac{W}{\alpha}$, where $\eta$ designates alpha recoil nuclei. On the basis of Madsen's data, Knipp and Ling calculated that about 66 percent of the ionization by a recoil particle from natural alpha decay is produced by recoil gas atoms which have reduced ionization efficiency.

Since fission fragments have a distribution in mass, in energy, and in effective charge, it is difficult using electric and magnetic fields to isolate those which have a definite mass and energy. Thus, information about $\Delta_f$ and $W_f$ are not available from an $E$ vs $I$ curve for a fragment of given mass. However, there is considerable indirect evidence that a fission fragment stopped in argon gas has a relatively large $a\Delta_f$.

Many studies of the fission process have been made using ionization chambers to measure the ionization produced by fission fragments when they are stopped in a gas.

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Ionization yields of the fragments are converted to energies by comparison with the ionization produced by an alpha particle of known energy stopped in the same gas. This characterization of the energy of fission fragments assumes that the $a_W$ for light fast particles is closely equal to that for slower heavy particles. The following pieces of evidence seem to indicate that this assumption is not valid for fission fragments stopped in argon gas.

First, the most probable total kinetic energy of fission which was obtained by means of ionization chamber experiments $^{13}$ was lower than that which was estimated from calorimetric measurement $^{14}$. Although several corrections involving neutron and photon energies have been applied to the calorimetric estimate of the kinetic energy, the difference between the values is regarded as significant.

Second, the mass distribution curve which was calculated from double ionization chamber data on fission

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$^{14}$ M. C. Henderson, Phys. Rev. 58, 774 (1940).
fragments is not in complete agreement with the mass distribution curve which was obtained from radiochemical analysis of fission products. After correction of the radiochemical mass distribution curve for the absence of ejected neutrons, the peaks of the ionization chamber mass distribution were found to be wider and farther separated than that from radiochemical data, as shown by Fig. 2. Brunton and Hanna suggested that the greater spacing between the mass peaks could be explained if the average energy per ion pair for the most probable heavy fragment, were 2 to 5 percent larger than the average energy per ion pair for the most probable light fragment. Leachman demonstrated that the greater separation of the mass peaks could be explained by an greater than by 3.7 percent. He analyzed the mass distribution curve from double ionization chamber data and made corrections for dispersions due to neutron recoils and instrumental errors, and the remaining discrepancy with the corrected radiochemical curve was attributed to difference in between light and heavy fragments.

Third, on the basis of a large energy loss to

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Fig. 2 Comparison of mass distribution curves
recoiling gas atoms by a slow heavy particle and of a reduced ionization efficiency of heavy recoil gas atoms, Knipp and Ling\textsuperscript{2} calculated the ionization defects for the most probable light and heavy fragments. They estimated the ionization defect for the light and heavy fragments in argon as $a_\Delta_{1f} = 2.5$ Mev and $a_\Delta_{hf} = 4.2$ Mev, respectively. On the same basis, they further showed that $W_{hf}$ should be larger than $W_{lf}$.

Fourth, Leachman\textsuperscript{17} obtained for fission fragments a velocity distribution curve in which the velocities of individual fragments were directly measured in a time of flight apparatus. When the velocity data were compared with the velocity distribution curve calculated from double ionization chamber data, see Fig. 3, they indicated that the kinetic energies of the fragments exceed those reported by ionization chamber measurements in argon by 5.7 Mev and 6.7 Mev for the most probable light and heavy fragments, respectively. These energy differences were explained by an $a_{lf}$ and $a_{hf}$ which exceeded by 6 and 11 percent, respectively, the $W_{\alpha}$ on which the energies from ionization chamber measurements were based.

\textsuperscript{17} R. B. Leachman, Phys. Rev. \textbf{87}, 444 (1952).
FIG. 3 COMPARISON OF VELOCITY DISTRIBUTIONS
Fifth, Leachman has shown that the greater widths of the peaks of the ionization chamber mass-distribution curve were explained by an 8 Mev half-width (full width at half-maximum) in the resolution of fission fragment energies in an ionization chamber filled with argon gas. Also the half-width of the energy resolution of the ionization chamber data estimated by the velocity-ionization analysis was about 9 Mev. The fact that this estimated dispersion was far greater than that anticipated by the theory of the fluctuations in the total number of ions produced by charged fragments indicated that energy loss processes which have larger fluctuations are present. Fluctuations in the number of recoiling atoms and in their ionization efficiency would result in relatively larger fluctuations in the total number of ions produced.

The results of the velocity distribution experiment give the most reliable evidence from the qualitative and quantitative standpoints for the variation of $W_f$. An increase of $W$ for fission fragments over that of alpha particles does not confirm the existence of an

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ionization defect for fission fragments since the energy-ionization curve for a fission fragment of given mass could be a straight line, instead of a curved line, passing through zero. However, the ionization defects calculated by Knipp and Ling from limited data are roughly in agreement with the energy differences calculated by Leachman from his velocity distribution experiment.

On the basis of the evidence listed above, it is not improbable that a non-linearity of the energy-ionization curve gives rise to an ionization defect for fission fragments stopped in argon gas.

For the case of fission fragments it was indicated that $\Delta_{1f} = 5.7$ Mev and $\Delta_{2f} = 6.7$ Mev. Since the secondary ionization efficiency of recoil argon atoms appears to play an important part in stopping of fission fragments, it is of interest to determine whether the secondary ionization efficiency is a function of the mass of the recoil atoms, and thus whether the $\Delta_f$ is a function of the mass of the stopping gas. From an analysis of the theory of the stopping of heavy charged particles, it is concluded that recoil gas atoms of smaller mass should have, on the average, a higher ionization efficiency.

It has been the purpose of this experiment to study
the changes in the magnitude of the ionization defect for fission fragments which were stopped in various gases. Comparison of the magnitude of the ionization defect between gases, and particularly between light and heavy gases, was expected to provide some further evidence on which to base theoretical considerations.
METHOD OF PROCEDURE

Working Equation

Since fission fragments which have a known mass, energy, and charge are not easily separated, $\Delta_f$ cannot be obtained directly from an $E_f$ vs $I_f$ curve. Rough theoretical and indirect experimental calculations, as listed previously, were made to obtain a value of $\Delta_f$. No similar calculations are available for other gases. Because naturally occurring alpha particles have relatively small ionization defects which are slowly changing functions of the mass of the stopping gas, they provide a basis for the comparison of the relative quantities of ionization produced by the stopping of a given fission fragment in different gases. An equation which gives $\Delta_f = h\Delta_f$ in terms of quantities that were measured experimentally can be derived from the definition of the ionization defect for a fission fragment and an alpha particle stopped in two gases, in this case argon and helium. The equation was obtained in terms of $E_\alpha$, $a^\Delta_\alpha$, $he^\Delta_\alpha$, $a^R$ and $he^R$, where $x^R$ is the ratio of the total ionization produced by a fission fragment to that of the alpha particle in a gas $x$.
From the definition of the ionization defect the following relations can be obtained for an alpha particle and a fission fragment stopped in argon and helium gases:

(1) \( a \Delta_\alpha = E_\alpha - (I_\alpha W')_a \)

(2) \( a \Delta_f = E_f - (I_f W')_a \)

(3) \( \text{he} \Delta_\alpha = E_\alpha - (I_\alpha W')_{\text{he}} \)

(4) \( \text{he} \Delta_f = E_f - (I_f W')_{\text{he}} \)

\[ x_{fY} x_{W'} \equiv (I_f W')_x. \]

Elimination of \( E_f \) between relations (2) and (4) gives

(5) \( a \Delta_f - \text{he} \Delta_f = (I_f W')_{\text{he}} - (I_f W')_a \).

\( a^R \) and \( \text{he}^R \) are given by the relations

(6) \( a^R = I_f^a / I_\alpha^a = (I_f W')_a / (I_\alpha W')_a \) and

(7) \( \text{he}^R = \text{he} I_f^a / \text{he} I_\alpha^a = (I_f W')_{\text{he}} / (I_\alpha W')_{\text{he}} \).

Combination of relations (1), (3), (5), (6), and (7) gives

(8) \( a \Delta_f - \text{he} \Delta_f = \text{he}^R (E_\alpha - \text{he} \Delta_\alpha) - a^R (E_\alpha - a \Delta_\alpha) \).
Assuming that the $a \Delta \alpha$ and $he \Delta \alpha$ are small compared to $E_{\alpha}$, the following working equation is obtained:

$$f \left( a \Delta f - he \Delta f \right) = E_{\alpha} \left( heR_f - aR_f \right).$$

Quantities on the right side of equation (9) were obtained from experimental measurements. The initial energy was available from magnetic deflection experiments $^{19}$, and the ratio of the fission ionization to that of an alpha particle was determined in the present experiment.

Equation (8) is valid for any two gases, and equation (9), of course, is valid when the ionization defects for alpha particles stopped in the gases are small compared to the initial energy of the alpha particles. For naturally occurring alpha particles the ionization defect in argon gas was found experimentally to be small compared to $E_{\alpha}$ $^{8,9}$. Ionization defects for alpha particles stopped in the other gases, which were used in this experiment, have not been measured. For the purposes of this experiment they have all been assumed to be small compared to $E_{\alpha}$. Since the ionization

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defects in argon gas were the best known, this gas has been used as a basis of comparison between the other gases. Values of the differences of the ionization defect between argon gas and each of the others have been calculated.

A description of the experimental method which was used to measure the ratio $x_R$ will now be undertaken.

Summary of the Experimental Method

A gridded parallel-plate ionization chamber which employed electron collection was used to measure the total ionization which was produced by a particle stopped in the chamber gas. The movement of electrons in the electric field between the grid and collector electrodes induced on the collector electrode a voltage pulse which was directly proportional to the number of ion pairs that were created by the particle. The voltage pulse from the ionization chamber was amplified in a linear amplifier and classified according to pulse height, or total ionization.

Since the energies of the most probable fission particles are greater than those of the alpha groups by more than a factor of ten, the pulse heights were
observed to be greater by approximately the same factor. The amplifier gain which would spread the fission pulse height distribution over the useable region of a pulse height analyzer system would give little detail to the shape of the pulse height distribution curve for alpha particles. Thus, when alpha particle distributions were studied, it was necessary to increase the gain of the amplifier over that which was used for fission particles. In order to compare the fission particle pulse heights with those of the alpha particles in the determination of \( R \), a pulse height calibrator was used to accurately determine the change in gain of the amplifier.

Fission fragments were obtained from a natural uranium source which was irradiated with neutrons from a linear accelerator using the \( D(D,\text{n})\text{He}^3 \) reaction at 300 Kev, and two groups of alpha particles were obtained from the same uranium source. By measuring the total ionization produced by individual fission fragments and by making a graph of the number of fragments versus ionization, an ionization distribution curve which was double-peaked was obtained. From this curve there were two characteristic fission fragments, the most probable heavy and light fragments, which were identified as the fission fragments corresponding to the peaks. The curve
for fission fragments was taken in the presence of the
alpha particles whose pulse heights had, however, neg-
ligible effect on those of the fission fragments. Not
only were the pulse heights of the alpha particles an
order of magnitude smaller than the fission pulses but
the pulses out of the amplifiers were approximately
100 microseconds in width and the rate of alpha decays
was 20 per second. Fission events occurred at the
rate of about one per second.

The ionization distribution curve for the alpha
particles from natural uranium was also double-peaked
due to the presence of two alpha groups, one from U_{234}
and the other from U_{238}, which have energies of 4.76 and
4.18 Mev, respectively. This curve for alpha particles
was obtained with the accelerator not operating and with
the room noise at a minimum.

Determination of the distribution peaks and the
pulse heights which corresponded to the most probable
particles in both the fission and alpha distributions
was accomplished by using special techniques which will
be described later. Values of \( x_{R_{1f}} \) and \( x_{R_{hf}} \) were
then obtained by using both the alpha particles from
U_{234} and those from U_{238} as the basis for comparison.
\( x_{R_{1f}} \) and \( x_{R_{hf}} \) represent \( x_{R} \) for the most probable
light and heavy fragment, respectively. A superscript of \textsuperscript{234} or \textsuperscript{238} will be used with \( x^R \) to designate the \( \text{U}^{234} \) or \( \text{U}^{238} \) as the basis of the ratio, respectively.
Ionization Chamber

Parallel-plate ionization chambers have been used extensively for detecting and measuring the ionization produced by particles. In one of its simpler forms the parallel-plate ionization chamber consists of two separated parallel plates in series with a resistance and a potential difference. The volume between the plates is filled with matter, usually gaseous. When ionization originates between the two plates, the charges move toward the plates under the influence of the electric field. The energy absorbed by the charges in moving along the electric field gives rise to a voltage pulse across the resistor. Formulations of the theory of pulse formation in parallel-plate ionization chambers, and in other types of ionization chambers, are found in many publications, i.e., Wilkinson and Corson and Wilson.

Ionization chambers are often designated as either slow or fast. A slow chamber depends upon the movement of positive or negative heavy ions to produce the voltage

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pulse, whereas a fast chamber depends upon the movement of electrons which are freed from the matter during the ionization process. Electrons in a given electric field have a drift velocity approximately 100 times greater than that of the heavy ions. Therefore, the time of formation of the voltage pulse is approximately 100 times shorter in a fast chamber. The magnitude of the voltage pulse which comes from the parallel-plate ionization chamber is too small to be observed without amplification; therefore, electron pulse amplifiers are often used to increase the pulse magnitude. With ionization chambers employing electron collection the clipping time of the pulse amplifier can be relatively shorter, compared to that for the slow chambers, and trouble with low frequency microphonics is considerably reduced. However, complete collection of electrons in an ionization chamber is accomplished only if electrons are not lost in passage through the matter to the collector plate. In the present experiment gaseous matter and electron collection were used, and a discussion of the loss of electrons before they were completely collected will be given later.

For a given number of ion pairs created between the plates of a parallel-plate ionization chamber, the magnitude of the voltage pulse depends upon the distribution
of the ion pairs in the volume between the plates and upon the ratio of the ion to the electron drift velocity in the gas. These two effects are very largely eliminated by a gridded ionization chamber which has a third electrode placed in a position to shield the collector electrode from the region in which the ion pairs are formed. Suitable electric fields are applied between the electrodes so that complete electron collection is accomplished. A description of the physical properties of the gridded parallel-plate ionization chamber which was used in this experiment will now be presented.

Fig. 4 shows a schematic diagram of the chamber and the associated apparatus which was mounted on it. The ionization chamber housing was cylindrical in shape with inside dimensions of 12 3/8 inches in diameter and 9 inches in depth. The wall and endplates of the ionization chamber housing were made of 3/8 and 1/2 inch brass stock, respectively. The upper endplate was silver-soldered to the chamber wall, and 12 steel bolts (H) 3/8 inch in diameter were used to apply pressure to a teflon gasket (G) between the lower endplate and the chamber wall to give a vacuum seal. The source electrode (C) was supported from the upper endplate by porcelain insulators which were attached to three adjustable sylphon assemblies (L).
FIG. 4 SCHEMATIC DIAGRAM OF THE IONIZATION CHAMBER
Negative voltage for the source was applied by means of a glass-to-metal terminal (J), and the electrical connection to the source electrode was maintained by a spring contact. A shield box (K) with a decoupling resistor and capacitance was placed over the glass-to-metal seal. The source plate (D) was covered with a collimator (E), and they were held in position on the source electrode by a clamping ring (F). Two sets of three porcelain insulators were used to support the grid (A) and the collector (B) electrodes from the lower endplate. The grid was normally grounded to the chamber housing, and the collector electrode was connected through the chamber housing to the preamplifier by means of a glass-to-metal terminal (M). The preamplifier (S) was located on the lower endplate along with a dual pressure gauge (Q), a gas purifier (N), and a vacuum valve (P) having a teflon gasket (R). The chamber was normally supported on its side by four rubber shock-mounts. The target chamber (U) of the linear accelerator was placed near the upper endplate of the ionization chamber so that a maximum number of neutrons intercepted the uranium source which was located on the source plate (D).

The base plate of the source electrode was machined out of 1/4 inch brass stock and had a diameter of 10 3/4
inches. A cylindrical brass skirt, which was 1 7/8 inches long and had 1/8 inch walls, was attached to the base plate. The skirt on the source electrode caused the equipotential surfaces in the grid-source volume, where the ionization was formed by the particles from the source, to be concave toward the grid and the collector electrodes. In this manner the electrons formed in this region did not escape detection by being lost to the chamber housing. For a given potential difference between the source and the grid electrodes, the strength of the electric field in the grid-source volume varied from that between two large parallel plates. Except near the edge of the skirt of the source electrode, the electric field was weaker than that for parallel plates, due to the Faraday cage effect. The base plate of the source electrode was 8 centimeters from the grid wires.

The source plate was 5 inches in diameter and 1/8 inch in thickness. Natural uranium was deposited over the area of the source plate to a thickness of approximately 60 micrograms per square centimeter, using a technique which will be described later.

The collimator was 5 inches in diameter and was constructed from .035 inch aluminum sheet metal. Approximately 500 holes of 5/32 inch diameter were punched
in the collimator. From the geometry of the collimator the maximum angle of emission of particles from the source was found to be 77 degrees from the normal. The alpha particles from $^{234}\text{U}$ had the longest range of the particles which were observed by means of the ionization chamber. The ranges in argon and helium gases at 760 mm Hg and 22 degrees centigrade were calculated from Livingston and Bethe and were found to be 3.6 and 20 centimeters, respectively. Minimum pressures of 380 and 2120 mm Hg for argon and helium gases, respectively, were found necessary to stop the wide-angle alpha particles from the edge of the source before they reached the skirt of the source electrode. A small part of the ionization, which was formed in the collimator holes where the electric field was relatively weaker, may not have reached the collector electrode. Since the specific ionization as a function of particle range differed markedly between alpha particles and fission fragments, the percentage of the total ionization lost in the collimator was not the same. However, the quantity $\frac{R - \text{he}R}{a}$ was a second order function of the differences in ionization which were lost in the collimator.

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holes, and no correction was made for it.

The collector electrode consisted of a 10 l/2 inch diameter brass disc which was 1/8 inch in thickness. This electrode was located 1.27 centimeters from the grid.

The grid structure consisted of .0036 inch diameter steel wires which were parallel to each other and spaced .080 inch apart. These wires were mounted on a brass ring which was 1/8 inch in thickness and had an inside and outside diameter of 10 5/8 and 11 5/8 inches, respectively. Narrow slots were machined in the outside edge of the ring so that one continuous length of wire was stretched back and forth across the ring to form the grid. However, due to warping of the ring under tension, the above-mentioned wires became slack as new wires were placed in position. To obtain a more uniform tension in the wires of the grid, it was convenient to place a second wire on the grid structure as the first was removed.

When voltage was applied between the grid and collector electrodes, mechanical vibrations of the relatively long grid wires gave rise to large-amplitude low-frequency electrical signals, commonly called low-frequency microphonics, which came out of the ionization chamber along with the electrical pulses from the particles. The frequencies of these microphonics were largely below
750 cycles per second. They were minimized by using shock absorbers to support the ionization chamber, by decreasing the noise in the room, and by designing an amplifier system which had lowered response at these frequencies.

Bunemann et al.\textsuperscript{22} studied the characteristics of a gridded parallel-plate ionization chamber, such as that used in the present experiment. They obtained an equation which gives the condition necessary to insure that no electrons formed in the grid-source volume were lost to the grid in passing through it to the collector. The field ratio is given by

\begin{equation}
Z = \frac{X_{gc}}{X_{gs}} = \frac{1 + \frac{\pi d}{\xi}}{1 - \frac{\pi d}{\xi}}
\end{equation}

where $X_{gc}$ and $X_{gs}$ are the electric fields in the grid-collector region and the grid-source region, respectively; $d$ is the wire diameter, and $\xi$ is the distance between adjacent wires. Bunemann, et al.\textsuperscript{22} also calculated an equation which indicated the inefficiency, $\sigma^-$, with which the grid shields the collector from the charge in the grid-source region. The equation is

(11) \[ \sigma \approx \frac{5}{2\pi d_{gc}} \ln \frac{5}{2\pi d}, \]

where \( d_{gc} \) is the distance between the grid and collector electrodes. For the present chamber the values of \( \sigma \) and \( \Xi \) were calculated to be 6.2 percent and 1.32, respectively.

The gas inside the ionization chamber was continuously purified by a method which was used by Jentschke and Prankl and which has been used by numerous investigators since that time. Convection currents which were induced by external heating were used to circulate the gas from the ionization chamber through an auxiliary chamber which contained a purifier material.

In the present case the purifier consisted of a closed tubular chamber which was attached in a vertical position to the endplate of the ionization chamber housing by means of copper pipes which were 3/8 inch inside diameter and approximately 6 inches long. The housing of the purifier was machined from stainless steel tubing which had 1/8 inch wall thickness and 3/4 inch inside diameter. The lower end of the purifier chamber was closed off permanently and the top was removable so that

\[ 23 \text{ W. Jentschke and F. Prankl, Phys. Z. 40, 706 (1939).} \]
the purifier material could be replaced. A teflon gasket was used to obtain a seal. Purifier material was contained in a stainless steel basket which was placed inside the purifier housing and which was mounted on the top of the purifier chamber by means of a closed stainless steel tube. The stainless steel tube was $\frac{3}{8}$ inch outside diameter, and it passed through the purifier material to the bottom of the basket. When the purifier chamber was assembled, a thermometer was inserted into the open end of the supporting tube for the basket and was used to measure the temperature of the purifier material.

The purifier assembly was heated by means of resistance wire which was coiled around the purifier housing and which was insulated from the housing by a layer of asbestos wrapped on a layer of glass. Several layers of asbestos were wrapped around the outside of the heater coil. A water jacket was attached to the purifier housing between the heater coil and the gasket.

The ionization chamber was pumped out and filled with gas through the sylphon vacuum valve which was shown in the schematic diagram. A teflon gasket was used to obtain a vacuum seal between the moveable sylphon structure and valve seat.

For the case of a parallel plate ionization chamber
with no grid, hereafter called the ungridded chamber, the
collection time, \( t \), for the ionization produced by a
particle emitted from the source electrode was given by

\[
(12) \quad t = \frac{d_{gs}}{v_{gs}},
\]

where \( d_{gs} \) was the distance between the source and
collector electrodes and \( v_{gs} \) was the electron drift
velocity in this region. The electron drift velocity
in a gas was known to be a function of the kind of gas
and of the ratio \( \frac{X}{P} \), where \( X \) was the field strength
in volts per centimeter in the region of the electrons and
\( P \) was the pressure of the gas in millimeters of mercury
(mm Hg). Rossi and Staub \(^{24}\) presented a summary of in-
formation on electron drift velocities in most of the
commonly used gases and gas mixtures. However, there were
some relatively large discrepancies between the results of
various experimenters for some of the common gases, par-
ticularly argon. Klema and Allen \(^{25}\) and Colli and
Facchini \(^{26}\) made some more recent measurements on argon

\(^{24}\) B. B. Rossi and H. H. Staub, Ionization Chambers

\(^{25}\) E. D. Klema and J. S. Allen, Phys. Rev. 77, 661
(1950).

\(^{26}\) L. Colli and U. Facchini, Rev. Sci. Instr. 23,
39 (1952).
and nitrogen gases and their mixtures. Colli and Pacchini found that the degree of purity of the argon played an important role in the magnitude of the drift velocity. Their values for the drift velocity in argon gas were as much as one-third lower than those of Klema and Allen. The purification system for the present experiment used the same purifying agent as that used by Colli and Pacchini.

In the case of a gridded parallel plate ionization chamber, hereafter called the gridded chamber, the collection time, $t_g$, for the ionization was given by the expression

$$t_g = \frac{1}{v_{gs} + \frac{d_{gc}}{v_{gc}}},$$

where $v_{gs}$ and $v_{gc}$ are the drift velocities for electrons in a gas at a given pressure and in the grid-source and grid-collector fields, respectively; $d_{gc}$ is the grid-collector distance, and $l$ is the projection along the electric field of the particle path length. The quantity $d_{gc}$ was constant for the ionization of each particle; whereas $l$ varied with the angle of emission of the particle from the source. Maximum $t_g$ occurred for particles emitted perpendicularly to the source, and the minimum was determined by the collimator covering the source. The second term of
Pulses out of the preamplifier were not shaped appreciably and were displayed on an oscilloscope. Collection times for the electrons in the ungridded and the gridded chamber were observed from the rise time of the pulses. In the present experiment the ionization chamber was changed from a gridded chamber to the ungridded by electrically connecting the grid and collector electrodes. Rise times were measured on a synchroscope (cathode-ray oscillograph, Du Mont type 303A) which had a calibrated sweep, and the measurements of the collection times for the ungridded chamber were accurate to about 20 percent. Measurements for the gridded chamber were less accurate, about 30 percent, because the rise times varied with the angle of emission of the particle from the source and were estimated for the average pulse.

Fig. 5 summarizes some of the calculated and observed rise times for the gridded and ungridded ionization chamber. In the figure, 1 is the projected length of the alpha particle path length, and it was calculated for those particles which come out of the source at an angle of 45 degrees. The drift velocity
### FIG. 5 OBSERVED AND CALCULATED PULSE RISE TIMES FOR GRIDDED AND UNGRIDDED CHAMBERS.

<table>
<thead>
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<th>GAS</th>
<th>P mm</th>
<th>L cm</th>
<th>X&lt;sub&gt;gs&lt;/sub&gt; VOLTS</th>
<th>X&lt;sub&gt;gs&lt;/sub&gt; CM PER</th>
<th>PULSE RISE TIME (μSEC)</th>
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<td>125</td>
<td>.29</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>63</td>
<td>.15</td>
<td>8</td>
</tr>
</tbody>
</table>

*Note: Data table includes various combinations of gas, pressure, and measurement conditions, with observed and calculated pulse rise times for gridded and ungridded chambers.*
of electrons, \( v_{gs} \), in a given gas and in an electric field is a function of \( X/P \). Values of \( v_{gs} \) for argon and nitrogen gases were obtained from the work of Colli and Facchini, and those for helium and neon gases from a table published by Wilkinson. Although mixtures of argon and carbon dioxide gases are not shown in the Fig. 5, the pulse rise times were observed to be very fast. Mixtures of 3 percent and 1/3 percent carbon dioxide in argon gas were studied at pressures ranging from 3 to 1/2 atmospheres. The mixtures at 1/2 atmosphere were observed in a gridded chamber to have the longest pulse rise times, which were less than 4 microseconds for an \( X/P \) value of about 1/10. This indicated a relatively high electron drift velocity for these mixtures. It was observed that in the same gas and under the same conditions for \( X/P \) the rise times in the ungridded chamber were always longer than those of the gridded chamber. The observed rise times were lower than those which were calculated for the same conditions. This was explained in the following way.

A large proportion of the particle path length was projected in the direction parallel to the electric field. In the case of the gridded ionization chamber, the pulse began to rise as soon as the first electron entered the
grid-collector region. However, the pulse would not be observed to rise until a relatively large amount of charge had entered the region and brought the pulse height above the noise level. Also, the rise of the pulse did not end until the last electrons, which originated near the source electrode, were collected. This small rise at the end of the pulse would not be observed. For the ungridded chamber the pulse would rise above the noise relatively rapidly since the movement of all of the charge was effective in producing the initial pulse rise. However, the rise at the end of the pulse would be even slower than in the gridded case since the last part of the charge was moving through a much weaker electric field. Rise times could be measured more accurately for particles the path length of which was perpendicular to the electric field.

The rise times for the alpha particles in the various gases appeared to be in line with those for pure gases.

Electronic Equipment

The value of $W$ for natural alpha particles which were stopped in various gases, including the rare gases, has been
experimentally measured by Jesse and Sadauskis. Of the gases used in this experiment, purified helium gas had the largest $W_\alpha$ value, which was 42.7 electron volts. Energies of the two prominent alpha groups which are emitted from natural uranium were given as 4.18 and 4.76 Mev. A 4.18 Mev alpha particle which was stopped in helium gas gave rise to approximately 100,000 free electrons. These electrons were attracted to the ionization chamber collector plate which had a capacity of 70 micromicrofarads, including the input capacity of the preamplifier. Voltage induced on the input of the preamplifier was calculated as roughly 225 microvolts. Since voltage pulses of this small magnitude could not be conveniently measured, it was necessary to amplify those coming from the ionization chamber. Fig. 6 shows a block diagram of the electronic amplifiers and auxiliary equipment which were used to produce, amplify, shape, and analyze the pulses.

Negative voltage for the source electrode was supplied to the ionization chamber by a high voltage power supply, and positive voltage for the collector electrode was passed through the input circuit of the

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FIG. 6    BLOCK DIAGRAM OF THE EXPERIMENTAL EQUIPMENT
preamplifier and was supplied by batteries. The voltage pulse which came out of the ionization chamber was amplified by means of a preamplifier and a main amplifier which had a limited frequency pass-band. Gain of the preamplifier and main amplifier system was adjustable so that output voltage pulses from the main amplifier were of the order of 25 volts. Alpha pulses stopped in helium gas required the greatest amplification, and fission fragments stopped in argon gas required the least.

Two systems for pulse height analysis were used in the course of the experiment. The purpose of each system was to classify voltage pulses into pulse height intervals and to make available a set of data from which a plot of number of events versus pulse height could be made. Each of the systems for pulse height analysis required that the voltage pulses from the main amplifier be shaped in the same manner and that the shaped signal be applied to it in a push-pull driving arrangement. The pulse lengthener circuit was used to give the pulses a shape which was suitable for accurate pulse height analysis, and the intensifier circuit was used in conjunction with the two pulse height analysis systems. Following the pulse lengthener circuit a push-pull
amplifier was used to further amplify the signal and to drive the pulse height analyzers. A more detailed discussion will now be made concerning the electronic equipment.

The negative high voltage supply for the source electrode consisted of a conventional radio-frequency regulated power supply which was variable from 200 to 5500 volts. Variation of the voltage over this wide range was accomplished by making the total voltage variable over a range of about 25 percent and then dividing the voltage across a string of resistors. Positive voltage for the collector electrode was obtained from four 300-volt batteries along with a set of batteries whose total voltage was 150 volts. Collector voltage was variable in steps of 150 volts.

Fig. 7 shows a circuit diagram of the preamplifier. It consisted of three tubes in a feedback loop of three isolated by a cathode follower which was used to feed the signals through a 30 foot coaxial cable to the main amplifier. The cathode resistor of the cathode follower was located at the input of the main amplifier. Direct current filament power of 6 volts was supplied to the preamplifier from a selenium rectifier power supply, and a conventional full-wave rectifier circuit provided the
FIG. 7 PREAMPLIFIER
plate voltage which was regulated by a 150 volt gaseous regulator tube. A parallel-T rejection filter was located between the feedback loop and the cathode-follower and was centered at 100 cycles per second. This filter was one of four filters which were used to decrease the low frequency response of the amplifier system. Half-power points in the frequency response curve of the preamplifier were located at 500 and 500,000 cycles per second which corresponded to a clipping time of 358 microseconds and a rise time of $\frac{7}{10}$ microsecond, respectively. Gain of the preamplifier was 75 at a frequency of 10,000 cycles per second.

When there was no voltage between electrodes of the ionization chamber, the noise at the output of the main amplifier was almost exclusively that arising from the first tube of the preamplifier. By exercising care in selecting the first tube of the preamplifier, a lowered noise level was obtained. The equivalent noise level of the first tube of the preamplifier was measured by observing the root mean square voltage of the noise level coming out of the main amplifier and dividing this by the gain of the amplifiers. Root mean square voltage was observed to be about 1 volt for an amplifier gain of 3.75 times ten to the fifth power. This
information gave an equivalent noise level in the first tube of the preamplifier of approximately 3 microvolts.

Since the rise times of pulses which originated in the ionization chamber were a function of the angle of emission of particles from the source, it was important that varying rise times did not result in varying pulse height of the amplified pulses. Two methods for making the pulse height of amplified voltage pulses relatively independent of the rise time of the pulse were discussed by Wilkinson. Both methods were discussed in terms of the clipping and rise times of the amplification system. First, the rise time of the amplifier was made short compared to the pulse rise time and the clipping time of the amplifier was made very long (approximately 50 times) compared to the slowest rise time of the pulses; and, second, the clipping and rise times of the amplifier were made equal and at least twice as long as the slowest rise time of the pulses.

The first method was rejected because the pulse rise times out of the ionization chamber were greater than 10 microseconds, and this long pulse rise time would require that the clipping time of the amplifier be relatively long (several hundred microseconds). An amplifier with such a clipping time would have good
response to low frequencies which arise from the microphonics generated by the long grid wires. The second method was adopted, and Fig. 8 shows a schematic diagram of the main amplifier which was designed to satisfy the conditions of the experiment.

The main amplifier consisted essentially of two feedback loops of three tubes with a cathode follower output. Tubes T-1, 2, 3 formed the first loop which was a conventional feedback amplifier having a gain of approximately 50. Tubes T-4, 5, 6 formed the second loop which had a narrow frequency pass-band and a peak gain of about 100. Three filter units were incorporated into the main amplifier. First, a parallel-T rejection filter which was centered at 8 kilocycles per second was placed in the feedback path of the second loop of three to provide a narrow frequency pass-band. Second, a parallel-T rejection filter which was centered at 60 cycles per second was placed between the second loop of three and the output cathode follower to further reduce the low frequency gain of the amplifier system. Third, a bridged-T rejection filter which was centered at 715 cycles per second was placed at the input of the main amplifier to remove a troublesome microphonic of this frequency which came from the ionization chamber.
FIG. 8 MAIN AMPLIFIER
Another parallel-T rejection filter which was centered at 225 cycles per second was located between the main amplifier and the pulse shaping circuit which followed and was used to further lower the low frequency response of the amplifier system. The frequency response curve for the main amplifier showed lower and upper half power frequencies at 5400 and 10,300 cycles per second. These frequencies corresponded to a rise time and a clipping time of about 30 microseconds.

The frequency response for the electronic system through the filter at the output of the main amplifier is shown in Fig. 9. This curve was obtained by feeding signals of constant magnitude from a variable frequency oscillator (Hewlitt Packard Model 650A) to the source electrode of the ionization chamber. Capacitive coupling between the source and the collector electrodes placed a signal on the grid of the first tube of the preamplifier. The output voltage as a function of frequency was read on a vacuum tube voltmeter (Simpson Model 266) attached to the output of the filter. The rise time and clipping time of the amplifier system were calculated approximately from the half-power frequencies obtained from the frequency response curve of the system. From the voltage plot of the frequency response curve of the present system, it was indicated
$f_1 = \text{LOWER HALF POWER FREQ. } \approx 5400 \text{ cps.}$

$f_2 = \text{UPPER HALF POWER FREQ. } \approx 10,300 \text{ cps.}$

$t_n = \frac{1}{3f_2} \approx 29.5 \mu\text{sec}$

$t_c = \frac{1}{2\pi f_1} \approx 32.5 \mu\text{sec}$

**FIG. 9** FREQUENCY RESPONSE CURVE OF THE AMPLIFIER SYSTEM
that the rise time and the clipping time were approximately the same and equal to about 30 microseconds. Experimentally the rise time and clipping times were observed to be approximately the same and equal to about 35 microseconds. This pulse was fed into a pulse lengthener and intensifier circuit which shaped the pulse for accurate analysis of pulse height by the pulse analyzer systems.

To simplify the pulse height analysis, which will be described in a later section, the pulse lengthener and intensifier circuit was used to provide a flat-topped pulse and a delayed intensifier pulse. The schematic diagram of the circuit is shown in Fig. 10, and its functions can be discussed in three parts. First, tubes T-1,2,3,4 constituted a peak reading voltmeter which employed two paralleled cathode-followers to charge a storage condenser through a diode and which had a cathode-follower output. Second, tubes T-5,6,7,8,9,10 were used to apply a discharge pulse to the storage condenser approximately 135 microseconds after the beginning of the incoming pulse. Thus, the rise time of the pulse coming out of the pulse lengthener was the same as that of the incoming pulse from the main amplifier. However, after following the incoming pulse up to its maximum
FIG. 10 PULSE LENGTHENER AND INTENSIFIER CIRCUIT
height, the pulse out of the pulse lengthener remained at the maximum height for about 100 microseconds and then dropped sharply to roughly zero. This produced a flat-topped pulse whose amplitude was proportional to that of the incoming pulse. Third, tubes T-5, 6, 7, 11, 12, 13 provided a positive intensifier pulse which was 60 volts in magnitude, 5 microseconds wide, and delayed by 45 microseconds from the beginning of the incoming pulse. A bias control in the Schmitt trigger circuit formed by tubes T-5, 6 was used to discriminate against the noise level and to start the delay functions as soon as the incoming pulse was above the noise level. The pulse from the pulse lengthener was conducted to a push-pull amplifier which was used to drive the pulse analyzer systems.

Fig. 11 is a schematic diagram of the push-pull amplifier, which was a Los Alamos Model 1000 amplifier that was biased asymmetrically to provide a maximum unsaturated push-pull swing of about 450 volts for positive input pulses. Each side of the amplifier had a voltage gain of approximately seven, and the frequency response curves showed half-power frequencies of 100 and 500,000 cycles per second corresponding to a clipping time and a rise time of about 1500 and 7/10 microseconds,
FIG. 11 PUSH-PULL AMPLIFIER
Pulses from the push-pull amplifier were applied to the two channel analyzer systems. One of these systems made use of a dual beam cathode-ray tube and Fig. 12 shows a schematic diagram of the oscillograph circuit. The pulses from the push-pull amplifier were applied to the deflector plates of one of the beams. The other beam was not deflected by the pulses and was used as a reference point. For testing purposes, the tube was used with a driven sweep which was provided by a Model 260 Los Alamos sweep circuit.

Since fission fragment ionizations were as much as 20 times larger than those of alpha particles which were emitted by natural uranium, it was necessary to increase the gain of the amplifiers by approximately 20 times when passing from a fission to an alpha particle analysis. An accurate measurement of the change in amplifier gain was imperative to obtain accurate results for the ratio of fission to alpha particle ionizations. Fig. 13 shows a schematic diagram of the circuit which was used to calibrate the gain of the amplifier. A Western Electric Relay Tube 275B was placed in the cathode branch of a multivibrator circuit which was set for a frequency of approximately 8 cycles per second. A direct current negative voltage supply was
FIG. 12 OSCILLOGRAPH CIRCUIT
FIG. 13 PULSE HEIGHT CALIBRATOR
placed in series with the contacts of the relay tube and with a condenser. As the relay contacts were closed, the .05 microfarad condenser was charged rapidly to the supply voltage and a negative pulse was obtained on the voltage divider across the condenser. The relay contacts closed for one-half cycle and then opened for one-half cycle. However, when the relay opened, the condenser discharged relatively slowly through a 500 microsecond time constant, and no positive pulse was observed. The voltage divider consisted of a precision 10,000 ohm resistance in series with a 10,000 ohm decade box which was shunted to 215.5 ohms. The decade box (General Radio Corporation GR 510F accuracy 1/10 percent) was found to have a good frequency response curve.

For alpha calibrations it was necessary to use supply voltages ranging from 3 to 5 volts, whereas voltages from 60 to 100 volts were applied to the relay during fission calibrations. A voltage divider was placed across the variable voltage supply and a potentiometer was used to monitor the magnitude of the voltages to about .02 percent.

In the calibration procedure a standard length of coaxial cable was used to conduct the calibration pulses from the calibrator to the source electrode of the ionization chamber. By placing the calibrator pulses on the
source electrode the amplification of all the electronic equipment was determined. The decade box was set on the highest position and the variable supply voltage was increased until the signal into the channel analyzer was larger than the particle pulses which were being calibrated. This voltage was then monitored using the potentiometer, and calibration pulses in ten equal steps across the channel analyzer were available by changing the sliding contact of the decade box.

The calibrator was checked for possible variation in the height of calibration pulses as a function of the supply voltage. This check was accomplished by setting the decade box at its maximum value and the supply voltage at a relatively low value. Then by decreasing the decade box in steps and increasing the supply voltage an equal amount, as determined by the potentiometer, the calibrator pulse height was observed to remain constant within the observational error of 1/10 percent over the supply voltage range from 1 to 100 volts.

Three different relay tubes were tested and no change in calibration pulse output was detected outside the experimental error of 1/10 percent.
Pulse Height Analysis

The magnitudes of the most probable ionizations for the fission fragments and for the alpha particles were obtained from distribution curves in which number of particles versus ionization were plotted. Accurate location of the ionization peaks required that many points be obtained on the sides of each peak. Under the best conditions for producing neutrons in this laboratory the fission rate, as observed from the ionization chamber, averaged about one per second. The large number of points which were necessary to form an ionization distribution curve and the slow rate of fission events ruled out the use of a single channel differential channel analyzer in taking data. It was highly desirable that the ionization of each fission particle that was stopped in the gas between the ionization chamber plates should be classified and used to form the ionization distribution curve. For this reason considerable time and effort were used in working with multiple channel analyzer systems.

As they became available, two multiple channel analyzer systems were used in the present work. First and foremost, all available data were recorded on film and later analyzed using a photoelectric scanning instrument. Second, a portion of the available data were
electronically classified in pulse height intervals and registered directly on a set of mechanical counters. The first system will hereafter be referred to as the photoelectric channel analyzer, and the second will be called the electronic channel analyzer.

The photoelectric channel analyzer was built by the Synchrotron Group of the Institute for Atomic Research and has been described in a report. In this method the pulses from the push-pull amplifier were displayed on an oscillograph tube in a special manner so that the pulse showed up as a round dot of light. The height of the dot above the baseline of the oscillograph beam was made directly proportional to the ionization which was collected by the collector plate of the ionization chamber. The face of the oscillograph tube was photographed on a continuously moving film using a Du Mont Fairchild Oscillograph Record camera. Linograph ortho film was used, and the film was moved in a direction which was parallel to the baseline of the oscillograph beam.

The action of the pulse lengthener and intensifier circuit was described previously, and the role of the

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flat-topped pulses and the intensifier pulse in the formation of the dots will now be developed. Normally the beam of the oscillograph tube was biased to the cut-off point, and the oscillograph was used with a driven sweep, or as a synchroscope. When an ionizing event took place in the ionization chamber, a flat-topped pulse, which had a rise time of about 35 microseconds and a flat-top for 100 microseconds, was displayed on the oscillograph screen, assuming that the beam was turned on by an intensifier pulse which lasted for the duration of the flat-topped pulse. However, if the delayed intensifier pulse from the pulse lengthener and intensifier circuit was applied to turn on the synchroscope beam for 5 microseconds after a 45 microsecond delay, one observed only a 5 microsecond length of the flat-top of the pulse. Upon removal of the sweep voltage from the oscillograph tube, the pulse showed up on the screen as a dot which had a duration of 5 microseconds. The dot was above the baseline by the height of the pulse, and it was located directly above the zero signal position of the oscillograph beam. Alpha particle pulses, fission fragment pulses, and alpha and fission calibration pulses were recorded on film as dots.
The oscilloscope screen was photographed with the camera lens set at f:2 and film drive speeds were varied to compensate for the frequency and the scattering of the pulses which were photographed. Alpha pulses came at the rate of about 20 per second and the pulse heights were concentrated in two relatively narrow peaks. A film drive speed of about 35 inches per minute was used for alphas. In contrast, the fission pulses came at the rate of about one per second and were spread over two relatively broad peaks so that a film drive speed of about 2 inches per minute was satisfactory. Calibration pulses for both the alpha particles and the fission fragments came at the rate of about eight pulses per second. However, the amplifier noise level at the higher gain position which was necessary to observe alpha particles was larger than that for fission fragments so that the alpha calibration pulses were scattered over a wider range. For this reason the film drive speed for the alpha calibration pulses and the fission calibration pulses were different and were taken as 12 and 18 inches per minute, respectively.

Linograph ortho film was obtained in daylight loading 100 foot rolls, and by loading the camera in a dark-room there were about 8 extra feet that were usable.
A typical alpha ionization distribution of 10,000 events was recorded on 25 feet of film, and the alpha calibration distribution required about 10 feet. For a fission ionization distribution of 20,000 events it was usual to use about 35 feet of film, and the fission calibration distribution was recorded on about 15 feet. A complete set of data for an alpha and a fission ionization distribution were recorded on one 100 foot roll of film, and the completed run consisted of an alpha distribution, alpha calibration, fission calibration, fission distribution, and a second fission calibration.

The film was processed in a Smith Film Development Outfit Model L35-100, and Eastman Kodak Developer D-19 was used.

The multiple channel analysis of the dots which were recorded on the film was performed by a photoelectric scanning device which is shown in the schematic diagram of Fig. 14. A source of light was collimated by an optical system so that a pin-point of light was focused on the plane of the film. In the horizontal plane and on the opposite side of the film from the light source, there was a second lens system which focused the illuminated portion of the film on a photomultiplier tube. The film was held in a film guide which was perpendicular
1, 2, 3, 4, 5, 6 - Mechanism for changing channels
7 - Light source
8 - First optical system
9 - Film guide
10 - Second optical system
11 - Light shield
12 - Photomultiplier tube
13 - Axis of the moveable arm
14 - Moveable arm

Fig. 14. Photoelectric Scanning Device
to the light beam, and a horizontal transport mechanism was used to draw the film through the guide in either direction at a constant rate. Thus, as the film was drawn through the film guide, each dot which interrupted the light beam sufficiently would produce a pulse in the output of the photomultiplier tube. Associated electronic circuits were used to discriminate against partial interruptions of the light beam and to count the larger interruptions.

The light source, the optical systems, and the photomultiplier tube were mounted on an arm which could be raised and lowered with respect to the film guide. Movement of the film through the film guide from one end to the other enabled the analyzer to record the number of dots which were located in a pulse height interval.

The photoelectric scanning operation was completely automatic in that the film transport mechanism reversed itself at the end of the film and at the same time actuated mechanisms which recorded the number of counts, cleared the counter, and raised or lowered the arm to scan the adjacent channel.

The channel width of the photoelectric scanner was controlled by the aperture of the photomultiplier tube and by the magnification of the optical system, and it
was made to be about .006 inch. The diameter of the
dots on the film was measured to be about .006 inch
also. It was observed that the dimensions of the images
on the negative film were reduced from the actual size
by a factor of six. When the baseline of the oscillo-
graph beam was set at one edge of the tube and the pulses
were restricted to the 3 inch diameter area in the
center of the oscillograph screen, the dots covered about
a 1/2 inch width on the film. Since each channel of
the photoelectric analyzer was about .006 inch in width,
there were roughly 85 channels to cover this range of
pulse heights.

In practice, the operation of the photoelectric
channel analyzer was carefully checked before each use
by observing large numbers of consecutive runs over the
same channel of a distribution. Further, all film was
analyzed at least twice and the results were averaged.

Typical distribution curves which were obtained by
use of the photoelectric channel analyzer are shown in
Figs. 37-42 in the section on results. The alpha
and the fission distributions were covered by about
25 and 65 channels, respectively.

The electronic channel analyzer made use of the
beam-deflection technique which has been discussed in the
literature 29. Special cathode-ray tubes (Du Mont K1159) which had ten collector electrodes mounted in a line across the end of the tube were obtained. A twenty channel analyzer was constructed using two of these tubes as the discriminating elements in the pulse height selection. The pulse lengthener and intensifier circuit which was used with the photoelectric channel analyzer also satisfied the requirements of the electronic channel analyzer now under discussion.

The flat-topped pulse from the pulse lengthener circuit was applied to the deflection plates of the special cathode-ray tube by the push-pull amplifier, and it deflected the normally biased-off beam to a collector electrode which corresponded to the pulse amplitude. During the flat-topped portion of the pulse, the beam was turned on by the delayed intensifier pulse, and a quantity of charge was deposited on the electrode. The signal imparted to this electrode then caused a count to be registered in that channel.

Each channel in the analyzer was about 4.5 volts in width. Thus, if the total bias voltage on the deflection

plates of the cathode-ray tube was of the order of 300 volts, a change of one channel on the analyzer corresponded to about a 1.5 percent change in the pulse height. By manipulation of the bias voltages on the deflection plates of the two tubes, the two sets of ten channels were located side by side so that 20 channels were spread across a range of pulse height.

The electronic channel analyzer was used almost exclusively to obtain the position of the alpha ionization peaks as a function of the voltages which were applied to the ionization chamber. For this type of study the electronic analyzer had a great advantage over the photoelectric channel analyzer because the position of the alpha ionization peak was determined almost immediately after recording a distribution. Suitable adjustments were then made in the chamber voltages and the position of the peak was checked again. For a total bias voltage of about 300 volts the width of one of the alpha ionization peaks was of such magnitude that it was well-covered by ten channels. Under these conditions a change in the alpha peak positions of about 2/10 percent was detected.

The electronic channel analyzer was not used for determining the fission ionization distributions because
20 channels distributed over the fission peaks would not give a sufficient number of points to draw the curve accurately. The fission ionization distribution curve could have been obtained by making two fission runs and setting the 20 channels across one peak and then the other. However, disadvantages of this procedure would be as follows: the Kevatron would run for 16 hours instead of 8 and give more than twice as much trouble; personnel would be exposed to neutron flux for twice as long; stability of the amplifiers would have to be maintained for the extra period; and in spite of this extended operational period, there would not be as many points on the ionization distribution curve as were obtained from the photoelectric channel analyzer for an 8 hour run.

From the standpoint of the present experiment, the advantages and disadvantages of the two multiple channel analyzer systems will be summarized. The electronic analyzer had the advantage of presenting the results for immediate observation, and this was almost indispensable in the study of the ionization chamber characteristics using alpha particles which were stopped in various gases. On the other hand, the photoelectric analyzer was very useful in obtaining fission ionization distributions because of the large number of channels which were spread
over the whole distribution and because the data for the
distribution were permanently recorded. Disadvantages
of the electronic analyzer were the fewer channels avail­
able and the inability to check the channel analysis
without making a complete new run. Disadvantages of the
photoelectric analyzer were the relatively long time
between the data procurement and the channel analysis
and the additional amount of work which was necessary to
obtain a final analysis.

Kevatron

The Kevatron is a 300 kilovolt linear accelerator
which was used to produce a large source of neutrons.
Neutrons were generated by accelerating deuterons in the
form of atomic and molecular ions down an evacuated
accelerator tube to impinge on a metal target. Originally,
zirconium metal was used to absorb deuterium gas and
the impregnated zirconium metal was bombarded with the
deuteron beam to produce neutrons by the reaction
D(D , n)He$^3$. However, it later became apparent that for
a 2 milliampere beam of about 90 percent molecular ions
the strength of the neutron source was relatively inde­
pendent of the type of target which was bombarded.
Since the neutron reaction has been observed to take
place at voltages as low as 60 kilovolts, the molecular ions, which have one-half the energy of the atomic ions, also make a contribution to the neutron flux. Targets of copper, brass, iron, and platinum appeared to produce as many neutrons as the impregnated zirconium. The independence of the target material with respect to neutron production was explained on the basis that the surface layer of the metal target absorbed and/or adsorbed part of the deuteron beam which struck it. An equilibrium condition for the metal targets was set up in a matter of a few hours of bombardment.

The magnitude of the neutron source appeared to increase directly with the deuteron beam current, and an average beam of about 2.5 milliamperes was used. The neutron source was measured to be somewhat larger than ten to the eighth power neutrons per second for the whole solid angle. When the ionization chamber was in place near the target of the accelerator, a fission rate of about 60 events per minute was observed in the chamber.
TECHNIQUES

In the course of the experiment a number of special techniques were used, and they will be described in the following under the topics of main amplifier, source preparation, gas purification, determination of saturation curves, and determination of ionization distribution peaks.

Main Amplifier

When the rise time of the amplifier was considerably longer than the maximum rise time of the incoming pulses, the magnitude of the amplified pulse was relatively independent of the changes in rise time of incoming pulses. Previously the characteristics of the main amplifier, which had a rise time equal to the clipping time and had both equal to 35 microseconds, were described in the section on electronic equipment. This narrow pass-band resulted in a large reduction in the noise level of the main amplifier, and the signal to noise ratio was thereby increased. Further, the long rise time characteristic of the amplifier enabled ionization which was moved through weaker electric fields,
such as that in the collimator holes, to contribute to the pulse.

Source Preparation by Spraying

The source of alpha particles and fission fragments was a thin film of natural uranium which was coated on the surface of a 5 inch diameter source plate. Because the source of neutrons was limited to about ten to the eighth power per second, the source plate was made as large as was practical so that a relatively large quantity of uranium was available for fission. It was essential that the uranium film be thin enough that a fission fragment which emerged from the film at the maximum angle allowed by the collimator lost only a small fraction of its energy within the film. In order that the maximum quantity of uranium be coated on the source plate without exceeding a predetermined surface density it was desirable that the thin film be as uniform as possible over the five inch diameter. Further, it was desirable that the source-making procedure be as quick and simple as possible, that there be little or no foreign material in the film, and that the thickness of the uranium film deposited should be predictable.
within about 10 percent.

A summary of some of the methods of making thin films is available in the literature. The methods which have been used most are the painting, dipping, vacuum evaporation, and electrodeposition. These methods were adequate for producing sources of small dimensions, but in each case it was difficult to obtain a uniform film over a large area.

A spray method for the production of thin uranium films which satisfied all of the conditions listed in the first paragraph was developed. It consisted essentially of dispersing a liquid uranium solution into a fine fog, conducting the fog into a closed container, and allowing the fog to settle out and coat a film on a source plate in the bottom of the closed container. A schematic diagram of the spraying apparatus is shown in Fig. 15.

A solution of 5 grams of uranyl nitrate in 20 grams of ethyl alcohol was dispersed into a fine fog by a De Vilbiss #40 Nebulizer. The fog was conducted into the top region of a closed vertical cylinder which had a diameter of 8 inches and a length of about 2.5 feet.

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FIG. 15 SOURCE SPRAYING APPARATUS
The source plate was located at the bottom of the cylinder. As the fog filled the cylinder and settled downward on the source plate, the uranium film was slowly formed. The thickness of the film deposited was a function of the spraying time, the concentration of the solution, the air pressure applied to the nebulizer, and the length of time the source plate was left in the fog after the spraying was stopped. A source thickness of about 60 micrograms of uranyl nitrate per square centimeter, as determined by alpha count in an ionization chamber, was obtained for a spraying time of 40 minutes, air pressure of about 2 centimeters of mercury, and a lay-over period of about 20 minutes after stopping the spray.

Uniformity of the uranium films deposited on a 5 inch diameter source plate was checked by counting alpha particles with an ionization chamber and by means of a radioautograph. An ionization chamber was used to count alphas from one inch diameter sections of the source plate. A radioautograph was made by laying a nuclear emulsion directly on top of the source plate. The processed radioautograph was studied under a microscope, and the alpha particles were counted for about one hundred fields of view. It was concluded that the films were uniform to at least 2 percent and 10 percent on a
macroscopic and microscopic scale, respectively.

Before using the source plate which was coated by a film of uranyl nitrate, it was heated to about 300 degrees centigrade in air to change the uranyl nitrate to uranium oxide.

Gas Purification

In working with ionization chambers which employ electron collection the importance of using very pure gases, or at least of knowing the kind and degree of impurity, to obtain consistent and accurate results cannot be over-estimated. Several investigators \(^{24-26}\) obtained different results in their measurements of the drift velocity of electrons in argon gas as a function of \(X/P\), where \(X\) and \(P\) are the electric field in volts per centimeter and gas pressure in millimeters of mercury, respectively. Wilkinson \(^{6}\) indicated that contaminations of oxygen and water vapor in counting gases, such as the noble gases, hydrogen, nitrogen, etc., could have either large or small effects upon the degree of electron collection. The effects vary with counting conditions such as the value and the type of counting gas. In the present work a continuous
purification method was used to increase the purity of the counting gases.

Common impurities of the inert gases which were commercially available were nitrogen, oxygen, hydrogen, and water vapor. In consideration of the work of Ruff and Hartman, and more recently Colli and Facchini, an alloy of calcium and magnesium metals was used as the purifying agent for the noble gases. Colli and Facchini examined the characteristics of a calcium-magnesium alloy which was composed of 10 percent magnesium and which was heated in the presence of some of the common impurity gases. They demonstrated that the alloy at a temperature of about 450 degrees centigrade combines relatively rapidly with the impurity gases listed above.

On the phase diagram of calcium-magnesium alloys it was observed that the eutectic temperature occurred at 445 degrees centigrade. At the eutectic temperature for an alloy of 10 percent magnesium metal in calcium metal, the phase diagram indicated that the liquid-solid phase consisted of about 60 and 40 percent solid and liquid, respectively. At 550 degrees centigrade the

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liquid-solid phase consisted of about 45 and 55 percent solid and liquid, respectively. The phase diagram showed the alloy to be completely in the liquid phase at about 700 degrees centigrade. It appeared evident that the alloy combined well with impurity gases when its temperature was at or above its eutectic temperature. Since there was a liquid phase present, it was probable that the surfaces of the alloy were in a process of continuous regeneration.

Calcium-magnesium alloy which was used in this experiment was obtained from the Metallurgy Group of the Ames Laboratory of the Atomic Energy Commission. The two metals were doubly distilled and the alloy was made in an argon atmosphere. Turnings of the alloy were placed in an argon atmosphere as they were machined in a lathe. After placing the turnings in the purifier chamber, they were outgassed at approximately 550 degrees centigrade at a pressure of about 0.01 microns for two days. The purifier temperature was then lowered to 475 degrees centigrade and the inert gas was admitted to the ionization chamber.

Using calcium-magnesium alloy from the same source
as that used in this experiment, Svec and Gibbs\textsuperscript{32} have confirmed the rapid absorption of nitrogen and oxygen at temperatures above 450 degrees centigrade.

Examination of the alloy after prolonged use in the stainless steel purifier assembly showed that the turnings which were adjacent to the stainless steel surfaces had wet and adhered to the container. Although the individual turnings of the alloy had not changed shape very much, those in the high temperature region were welded together into one large mass.

Considerable difficulty was encountered in the design of the purifier chamber, particularly those parts which were exposed to the hot calcium-magnesium alloy. At temperatures of approximately 450 degrees centigrade, it was observed that the alloy reacted with brass and with silver-soldered joints, but not with stainless steel. For this reason the purifier chamber was constructed from stainless steel in such a manner that no silver-soldered joints were exposed to the hot alloy.

Purification of nitrogen and hydrogen gases was not done with the calcium-magnesium alloy because of the absorption of the gases themselves. Hydrogen gas

\textsuperscript{32} H. J. Svec and D. S. Gibbs (Private Communication in June, 1953).
was purified by running the purifier at about 500 degrees centigrade and adding hydrogen gas until the alloy stopped absorbing it. It was assumed that the alloy was changed to a hydride, and the hydride was then used as the purifying agent. Large quantities of hydrogen were absorbed in converting the metals to the hydrides. Following the use of hydrogen as a counting gas, nitrogen was purified with the hydrogen-converted alloy which was held at a temperature of about 300 degrees centigrade. A mass spectrometer analysis of the nitrogen gas, which had been purified, showed that no impurities were present within the experimental error of 1/100 percent. Also several mass spectrometer analyses of purified argon gas revealed no impurities were present.

Determination of Saturation Curves

In a gridded parallel-plate ionization chamber employing electron collection, the effects which interplay to determine the pulse height are as follows: capture of electrons by the grid wires, multiplication of electrons about the grid wires, drift velocity of the electrons, and electron attachment and recombination. Wilkinson discussed each of these effects as applied to ionization chambers, proportional counters, and
Geiger counters. Fig. 16 is a schematic diagram of an ionization chamber, and it indicates some of the quantities which will be used in this discussion.

The ratio of fields which was necessary for complete collection of electrons was easily achieved in the present ionization chamber. Wilkinson mentioned that multiplication of electrons in parallel-plate ionization chambers was not likely to arise since $X/P$ equal to one was not usually exceeded. However, for a gridded parallel-plate ionization chamber, the value of $X/P$ can become quite large around the grid wires. In this experiment, electron multiplication was definitely present for purified argon gas, and it probably took place around the grid wires where $X_{gc}$ and $X_{gs}$ were much stronger.

Drift velocities of electrons in various gases were available in the literature. With a decrease in $X_{gs}$ and $X_{gc}$ the drift velocity decreased and the pulse rise time increased. When the rise time of the pulse became about one-half as long as the rise time of the amplifier, there was a pulse height decrease which was due to the amplifier characteristics.

Saturation for alpha particles or fission fragments was taken to mean that all the electrons which were
Vgs — GRID-SOURCE POTENTIAL DIFFERENCE
Vgc — GRID-COLLECTOR POTENTIAL DIFFERENCE
dgs — GRID-SOURCE DISTANCE
dgc — GRID-COLLECTOR DISTANCE
Xgs — GRID-SOURCE FIELD
Xgc — GRID-COLLECTOR FIELD

FIG. 16  IONIZATION CHAMBER WITH GRID
created in the stopping of the particle in the gas were removed from the gas without electron attachment or recombination. Experimentally, saturation for a given particle in a gas was shown by saturation curves in which the pulse height was obtained as a function of the source field, \( X_{gs} \). When the pulse height remained constant for further increase in the field, it was assumed that the effects of electron attachment and recombination were eliminated for that particle, or at least were constant.

In an ungridded parallel-plate ionization chamber a decrease of pulse height with decrease of \( X_{gs} \) was due to either the increase of electron attachment and recombination or the increase in the rise time of the pulses, or both. The presence of a third electrode in the gridded parallel-plate ionization chamber decreased the pulse rise time effect but introduced the additional effects of capture of electrons by the grid wires and multiplication of electrons about the grid wires. When multiplication of electrons about the grid wires was present, it was found, in general, to be a function of the higher field, \( X_{gc} \). Since saturation curves were taken with constant \( X_{gc} \), the shapes of the saturation curves were not visibly affected by the multiplication. For a given saturation curve the capture of electrons by the grid wires was eliminated by choosing \( X_{gc} \) large
enough, compared to the largest $X_{gs}$, so that the ratio of fields was not lower than $xZ_m$, the minimum ratio of fields for complete electron collection in a gas $x$. The variation of $xZ_m$ between gases will be discussed later.

Providing the effects of multiplication and ratio of fields were eliminated or held constant, a decrease in pulse height with decreasing of the source field was due to either the onset of electron attachment and recombination or the rise time increase, or both. In the gases which were used, relatively flat saturation curves were obtained at voltages which were within the limits of the breakdown voltages.

Saturation curves for alpha particles in the various gases were obtained through the use of the electronic channel analyzer. Ten channels of the analyzer were spread over the upper peak of the uranium alpha particle distribution. The half-width of the alpha peak on the channel analyzer was about five channels. In the determination of the pulse height of the alpha particle, the channel analyzer was operated until there were about 600 counts in the most probable channel. A median was calculated for each distribution and this median value was taken to be the position of the most probable alpha ionization. As $X_{gc}$ and $X_{gs}$ were changed in the ionization chamber, the changes in the value
of the median were interpreted as changes in the pulse height of the alpha particle.

From an examination of the scattering of the median values for a large number of distributions which were taken for constant chamber conditions, it was determined that a change in pulse height of about 2/10 percent was outside of the observational error.

In the study of the multiplication effect for alpha particles in various gases, the electronic channel analyzer was used to locate the changes in position of the ionization peaks.

Saturation curves for fission fragments in the various gases were established by using the photoelectric channel analyzer. The peaks of the distribution were obtained using the methods of the next section.

Effects of multiplication and ratio of fields around the grid wires were eliminated from the ionization chamber by electrically tying the grid and collector electrodes together and using it as a two electrode chamber. The field strength around the grid wires was greatly reduced by the close proximity of the collector plate at the same potential as the grid wires. Thus, the effects of rise time and of electron attachment and recombination were isolated from the others. The disadvantage of this expedient was the loss of
resolution for particles because of the relatively large solid angle for particle emission from the source. However, the resolution for the alpha particles remained good enough to obtain saturation curves. Curves for both the gridded and ungridded ionization chambers are shown in Fig. 17. Fig. 17a shows the saturation curves for the gridded and ungridded chambers to be approximately the same for 1/2 atmosphere of purified argon. The ungridded saturation curve is somewhat depressed at the low $V_{gs}$ values because of the increased pulse rise time (see Fig. 5). Fig. 17b shows the curves for purified argon gas at 1 atmosphere of pressure. The difference between the ungridded and gridded curves is very marked at the low $V_{gs}$ values, and it is due in part to the relatively larger differences in pulse rise time between the two chamber conditions at the increased pressure (see Fig. 5). Fig. 17c shows the saturation curves for a mixture of argon gas plus 3 percent carbon dioxide at a pressure of 1 atmosphere. Addition of a small percentage of carbon dioxide gas to the argon gas increased the electron drift velocity of the mixture, over that of pure argon, by about a factor of ten. The increased drift velocity resulted in relatively shorter pulse rise times for both the gridded and ungridded chambers. The two curves are essentially identical except at the lowest values of $V_{gs}$.
FIG. 17 A
ARGON GAS
400 mm Hg
○ GRIDDED CHAMBER
△ UNGRIDDED

FIG. 17 B
ARGON GAS
740 mm Hg
○ GRIDDED CHAMBER
△ UNGRIDDED

FIG. 17 C
ARGON + 3% CO₂
740 mm Hg
○ GRIDDED CHAMBER
△ UNGRIDDED

Vgs (1000 VOLTS OR X/P (.313) VOLTS/CM/MM Hg)

RELATIVE PULSE HEIGHT IN PERCENT

Vgs (1000 VOLTS OR X/P (.169) VOLTS/CM/MM Hg)

FIG. 17 SATURATION CURVES FOR GRIDDED AND UNGRIDDED CHAMBERS
where the drift velocities were slower and the rise times correspondingly longer. Fig. 17 indicates that the decrease in pulse height in argon gas with decrease of $V_{ga}$ was largely due to the rise time effect, rather than to electron attachment and recombination.

When the rise time of an amplifier is equal to the clipping time, Wilkinson has shown that the relative output pulse height from the amplifier as a function of input pulse rise time is given approximately by the expression

$$1 - \frac{s^2}{24},$$

where $s$ is the ratio of the pulse rise time to the amplifier clipping time. In the present experiment the amplifier rise time and clipping time were equal and somewhat greater than 30 microseconds. Since the particle path lengths for fission fragments were roughly two-thirds as long as those of the alpha particles, the rise times of the fragments averaged about one-third faster. In the case of argon gas at 1/2 atmosphere, the alpha particle rise time of about 15 microseconds resulted in about a 1 percent drop in pulse height compared with a fission fragment drop of about 1/2 percent. This differential effect between alpha particles and fission fragments gave rise to a small increase in the ratio of the most probable fission to alpha particle ionizations, and consequently increased the most probable fission fragment energies by no more than about 1/2
percent. Of the gases which were used in this experiment the argon gas at 1/2 atmosphere was calculated to give the largest differential effect. From the consideration of the rise times only the saturation curve for fission fragments would be expected to be constant over a slightly wider range of $V_{gs}$ than that of alpha particles.

The field ratio which was necessary for complete electron collection was investigated by taking observations on pulse height as a function of $X_{gs}$, holding $X_{gc}$ constant. $X_{gs}$ was increased until the pulse height started to decrease relatively rapidly. Curves from which the ratio of fields were calculated for various gases will be shown in a later section.

The multiplication effect was investigated by varying $X_{gc}$ and holding $X_{gs}$ at a constant value which was low enough to insure that the field ratio did not go below $x^{-m}$ over the range of $X_{gc}$. Examples of the multiplication curves will be given in a later section.

**Determination of Distribution Peaks**

Ionization distribution curves for alpha particles and for fission fragments were obtained through the use of the photoelectric channel analyzer. Fig. 37 shows an alpha
ionization distribution curve for argon gas at a pressure of 400 millimeters of mercury, and Fig. 38 shows a fission ionization distribution curve for the same gas. In order to accurately calculate the ratio of the most probable fission ionizations to one of the most probable alpha ionizations, it was necessary to determine the peaks of the distribution curves as accurately as possible. The accurate location of the peaks in both the alpha and fission ionization distribution curves, particularly the location of the heavy fission fragment peaks, caused some concern. Two methods were used to locate the peaks of the fission ionization curves. The first one, which was also used to locate the alpha ionization peaks, was dependent on those points which made up the sides of the peaks. The second one, which was used only on the fission ionization distributions, made use of most of the points on the distribution curve in the determination of the two peak positions.

In the first method a curve was drawn through the points of the distribution by mentally making calculations to keep the deviations at a minimum. Straight lines were then drawn through those points which were located around the inflection point on each side of the peak. A median line was constructed between the two straight lines which passed through the inflection points on either side of the peak.
The intersection of the median line with the ionization distribution curve was taken to be the most probable ionization associated with the peak. This method of locating the most probable ionization was quite insensitive to small error in the shape of the cap on the peak. A check on the reliability of this method was obtained by comparing the results of two independent analyses of the data which were recorded on a film. In fact, the complete data on four films were analyzed on two occasions, and the most probable ionization peaks for the alpha and the fission distribution curves were obtained. Fig. 13 shows the agreement between the results of the original and the repeated analysis for two complete runs in each of the gases, argon and helium. The agreement between the original and repeated analyses was observed to be better than that between the data which were obtained on different film using the same gas.

The second method for determining the most probable ionizations involved using most of the points of the distribution to locate a median for each peak. To find a median for each peak it was necessary to use a reliable criterion to divide the points of the fission distribution curve into two groups, the light and the heavy fission fragments. Since the upper edge of the light fragment ionization peak was observed to drop to zero relatively rapidly in all
<table>
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<th>ANALYSIS</th>
<th>METHOD I</th>
<th>METHOD II</th>
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<td>MOST PROBABLE PULSE HEIGHT</td>
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<td>IN MILLIVOLTS</td>
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</table>

FIG. 18 ORIGINAL AND REPEATED DATA COMPARISON
cases, the straight line which was fitted to the six or eight points located about the point of inflection of this edge was extrapolated to zero counts. The extrapolated value of the pulse height represented an ionization which was close to that produced by the most energetic light fission fragment, and it was very consistent between fission distribution curves in the same gas, as is shown in the Fig. 18. The light fragment ionization peak was separated, for the purposes of the median calculation, from the heavy by taking 74 percent of the extrapolated value and considering all counts above and below that ionization value to be in the light and heavy peaks, respectively. The medians for the light and heavy peaks of each ionization distribution curve were then calculated using all points that exceeded 5 and 10 percent of the height of the light fragment ionization peak, respectively. In order to obtain a most probable light fragment median value which was reasonably close to that obtained in the first method, a pseudo median was calculated in which the most probable ionization was taken to be the point at which 45 and 55 percent of the counts were above and below, respectively. The consistency of this method of locating the most probable ionizations was checked by applying the method to the original and the repeated analyses that were available for the two complete runs in
each of the gases, argon and helium. The agreement between the original and repeated analyses, as shown by Fig. 18, was again observed to be better than that between the data which were obtained on different films using the same gas.

The general results which were obtained from the two methods of locating the most probable ionizations were in good agreement. They will be discussed further in the following sections.
RESULTS

The multiplication curves which were obtained for purified argon and neon gases at various pressures are shown by Figs. 19 and 20.

Figs. 21-33 show saturation and ratio of field curves for alpha particles which were stopped in various gases and gas mixtures. Curves are shown for argon, helium, nitrogen, neon, carbon dioxide, argon plus 3 percent carbon dioxide, argon plus 1/3 percent carbon dioxide, and argon plus 5 percent nitrogen.

Graphs of electron temperature versus $X/P$ for argon, helium, neon, and nitrogen are shown in Fig. 34. These curves were obtained from the work of Townsend and Bailey as described by Rossi and Staub.

Fig. 35 summarizes the information which was obtained from Figs. 21-33 and which was relative to the minimum ratio of fields for complete electron collection, $xZ_m$. The use of information on electron temperatures obtained from Fig. 34 results in Fig. 35 which demonstrates a correlation between diffusion of electrons and $xZ_m$ for a gas.

Fission saturation curves for each of the gases which were used in this experiment are shown in Fig. 36.

Figs. 37-42 are distribution curves for the alpha
particles and the fission fragments stopped in argon, helium, and nitrogen gases. These curves are representative of those obtained for all the gases and gas mixtures.

Fig. 43 consists of six pages of tables which summarize the data and calculations to compare the ionization defects of fission fragments in various gases to that in argon. These tables contain the information relative to the experimental conditions, the most probable alpha ionizations, the most probable fission ionizations using Methods 1 and 2, the ratios of most probable fission to alpha particle ionizations using Methods 1 and 2, the most probable fission energies using Methods 1 and 2, the characteristics of alpha and fission distribution curves, and the ionization defects as calculated using Methods 1 and 2.

Fig. 44 is used to compare the literature values of $\chi^2$ with those calculated from the most probable alpha ionizations of the present experiment.

A summary of the error analysis is given in Fig. 45. The table at the top of the figure summarizes the estimates of the random errors and shows the total random errors associated with the most probable ionizations. The center table shows the estimated and calculated errors for the most probable fission energies. In the extreme lower left corner of the figure, the estimated errors for the average
fission energies are tabulated. The extreme lower right corner shows the errors which were estimated for the differences between the fission fragment ionization defect in argon gas and that in other gases.
FIG. 19 MULTIPLICATION CURVES FOR PURIFIED ARGON GAS
FIG. 20 MULTIPLICATION CURVES FOR PURIFIED NEON GAS

- $V_{gs} = 480$ VOLTS
- $V_{gs} = 525$ VOLTS

Relative Pulse Height (Percent) vs. $V_{gc}$ (Volts)

Equations:
- \( \frac{X_{gs}}{P} = \frac{V_{gs}}{8P} \)
- \( \frac{X_{gc}}{P} = \frac{V_{gc}}{1.27P} \)
FIG. 21 SATURATION CURVES AND RATIO OF FIELDS FOR PURIFIED ARGON GAS AT 400 AND 425 mm Hg
FIG. 22 SATURATION CURVES AND RATIO OF FIELDS FOR PURIFIED ARGON GAS AT 740 mm. Hg

\[ X_{gs} \frac{P}{P} = 0.46 \]

\[ X_{gs} \frac{P}{P} = 0.64 \]

\[ Z = \frac{6.3 V_{gc}}{V_{gs}} \]
FIG. 23 SATURATION CURVES AND RATIO OF FIELDS FOR PURIFIED ARGON GAS AT 1400 mm. Hg

\[ Z_m = \frac{6.3 V_{gc}}{V_{gs}} \]

\[ Z = \frac{V_{gs}}{P} \]

\[ X_{gs} = \frac{V_{gs}}{8P} \]
\[ V_{gc} = 1200 \text{ VOLTS} \]

\[ X_{gs} = \frac{V_{gs}}{P} = 0.26 \]

\[ Z = \frac{6.3 \times V_{gc}}{8P} \]

**FIG. 24 SATURATION CURVE AND RATIO OF FIELDS FOR PURIFIED HELIUM GAS AT 2200 mm Hg**
FIG. 25 SATURATION CURVES AND RATIO OF FIELDS FOR PURIFIED NITROGEN GAS AT 425mm Hg
FIG. 26 SATURATION CURVES AND RATIO OF FIELDS FOR PURIFIED NEON GAS AT 840 mm Hg
FIG. 27 SATURATION CURVES AND RATIO OF FIELDS FOR PURIFIED NEON GAS AT 1580 mm Hg

- Ne $V_{gc} = 620$ VOLTS
- Ne $V_{gc} = 390$ VOLTS
- Ne $V_{gc} = 300$ VOLTS

$Z_m = 2.03 \quad \frac{X_{gs}}{P} = 0.07$

$Z_m = 2.08 \quad \frac{X_{gs}}{P} = 0.09$

$Z = \frac{6.3 V_{gc}}{V_{gs}}$
FIG. 28 SATURATION CURVES FOR ARGON + 3% CARBON DIOXIDE AT VARIOUS PRESSURES

Vgs (VOLTS)

RELATIVE PULSE HEIGHT (PERCENT)

A + 3% CO₂
Vgs=1200 VOLTS

- X 2200 mm. Hg
- △ 1500 mm. Hg
- ○ 740 mm. Hg
- □ 425 mm. Hg
$2m = 1.55$

$Z_m = 1.70$

$X_{gs} = .65$

$A + 3\% \text{ CO}_2$

$\frac{X_{gs}}{P} = .62$

$Z = \frac{6.3 V_{gc}}{V_{gs}}$

FIG. 29 SATURATION CURVES AND RATIO OF FIELDS FOR ARGON GAS + 3\% CARBON DIOXIDE
FIG. 30 SATURATION CURVES AND RATIO OF FIELDS FOR ARGON GAS + 3% CARBON DIOXIDE

\[ X_{\text{gs}} = \frac{V_{\text{gs}}}{8P} \]
\[ Z = \frac{6.3 V_{\text{gc}}}{V_{\text{gs}}} \]

- 2200 mm Hg, Vgc = 1200 VOLTS
- 2200 mm Hg, " = 900 "
- 1500 mm Hg, " = 1200 "

\[ \bar{Z}_m = 1.51 \]
\[ \frac{X_{\text{gs}}}{P} = 0.28 \]
\[ \bar{Z}_m = 1.56 \]
\[ \frac{X_{\text{gs}}}{P} = 0.21 \]
\[ \bar{Z}_m = 1.55 \]
\[ \frac{X_{\text{gs}}}{P} = 0.41 \]
FIG. 31 SATURATION CURVE AND RATIO OF FIELDS FOR CARBON DIOXIDE GAS AT 425 mm. Hg

\[ Z_m = 1.45 \]
\[ \frac{X_{gs}}{P} = 1.54 \]

\[ Z = \frac{6.3 V_{gc}}{V_{gs}} \]
FIG. 32 SATURATION CURVES AND RATIO OF FIELDS FOR ARGON + 1/3% CARBON DIOXIDE AT VARIOUS Pressures
FIG. 33 SATURATION CURVES AND RATIO OF FIELDS FOR ARGON + 5% NITROGEN GAS AT 425 mm Hg
Fig. 34: Electron Temperature versus $\frac{p}{X}$

(Average Energy of Electrons / Thermal Agitation Energy)

Symbols:
- $N_2$
- He
- Ne
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<th>Xgs V/cm</th>
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<td>1.22</td>
<td>2</td>
<td>.003</td>
<td>.00</td>
<td>.00</td>
<td>1.45708</td>
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</table>

FIG. 35. CORRELATION OF Zm WITH ELECTRON DIFFUSION IN GASES
FIG. 36 FISSION SATURATION CURVES
FIG. 37 ALPHA DISTRIBUTION AND CALIBRATION CURVES IN ARGON GAS AT 400 mm Hg
RUN NO. 1

I_{LF} = 752.2 \text{ mv}
I_{HF} = 491.1 \text{ mv}

E_{LF} = E_{\alpha} R_{LF} = 92.9 \text{ mev}
E_{HF} = E_{\alpha} R_{HF} = 60.7 \text{ mev}

CALIBRATION CURVE

I_{R} = -18.68 + 0.2816 I

FIG. 38 FISSION DISTRIBUTION AND CALIBRATION CURVES IN ARGON GAS AT 400 mm Hg
RUN NO. 3

1234 = 23.61 mv
1238 = 20.75 mv

CALIBRATION CURVE

IR = -25.60 + 10.18 I

FIG. 39 ALPHA PARTICLE DISTRIBUTION CURVE IN HELIUM GAS AT 2200 mm Hg
RUN NO. 3

\( I_{LF} = 458.8 \text{ mv} \)
\( I_{HF} = 309.1 \text{ mv} \)
\( E_{LF} = 92.5 \text{ mev} \)
\( E_{HF} = 62.0 \text{ mev} \)

\[ I_R = -18.59 + 0.5083 I \]

FIG. 40 FISSION IONIZATION DISTRIBUTION CURVE IN HELIUM GAS AT 2200 mm Hg
RUN NO. 7

$l_{234} = 26.84 \text{ mv}$

$l_{238} = 23.58 \text{ mv}$

CALIBRATION CURVE

$\ln = -20.43 + 7.9601$

FIG. 41 ALPHA PARTICLE IONIZATION DISTRIBUTION CURVE IN NITROGEN AT 425 mm Hg
RUN NO. 7

ILF = 503.2 mv
IHF = 325.9 mv
ELF = 89.2 mev
EHF = 57.8 mev

CALIBRATION CURVE

$I_R = -18.01 + 0.3959 \, I$

FIG. 42 FISSION IONIZATION DISTRIBUTION CURVE IN NITROGEN GAS AT 425 mm Hg
<table>
<thead>
<tr>
<th>RUN NO</th>
<th>GAS</th>
<th>PRESS. mm Hg</th>
<th>NO. OF FISSION EVENTS</th>
<th>$X_{ac}$ VOLTS/PER cm</th>
<th>$X_{gs}$ VOLTS/PER cm</th>
<th>Z</th>
<th>Zm</th>
<th>MOST PROBABLE IONIZATIONS IN MILLIVOLTS (METHOD I)</th>
<th>EXTRA. PULSE HEIGHT MILLIVOLTS</th>
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<tbody>
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<td>400</td>
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<td>827</td>
<td>325</td>
<td>2.55</td>
<td>2.2</td>
<td>38.38</td>
<td>751.1</td>
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<tr>
<td>2</td>
<td>A</td>
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<td>20,000</td>
<td>827</td>
<td>325</td>
<td>2.55</td>
<td>2.2</td>
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<td>755.0</td>
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<tr>
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<td>He</td>
<td>2200</td>
<td>30,300</td>
<td>945</td>
<td>475</td>
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<td>1.7</td>
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<td>459.3</td>
</tr>
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<td>4</td>
<td>He</td>
<td>2200</td>
<td>28,700</td>
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<td>475</td>
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<td>1.7</td>
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<td>24,400</td>
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<td>2.2</td>
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<td>N$_2$</td>
<td>425</td>
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<td>945</td>
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<td>26.84</td>
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<td>595</td>
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<td>15,200</td>
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<td>Ne</td>
<td>1580</td>
<td>17,000</td>
<td>472</td>
<td>180</td>
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<td>2.1</td>
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<td>11</td>
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<td>1180</td>
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<td>1.7</td>
<td>36.76</td>
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FIG. 43a EXPERIMENTAL CONDITIONS AND MOST PROBABLE ALPHA AND FISSION IONIZATIONS USING METHOD I
### Ratios of Most Probable Ionizations ($xR$)

<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>$^{234}\text{R}_{1f}$</th>
<th>$^{238}\text{R}_{1f}$</th>
<th>$^{234}\text{R}_{hf}$</th>
<th>$^{238}\text{R}_{hf}$</th>
<th>$E_{234}$</th>
<th>$E_{234}$</th>
<th>$E_{238}$</th>
<th>$E_{238}$</th>
<th>$E_{238}$</th>
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<td>14.47</td>
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<td>60.5</td>
<td>59.4</td>
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<td>22.06</td>
<td>12.48</td>
<td>14.12</td>
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<td>59.4</td>
<td>59.0</td>
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<td>22.13</td>
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<td>14.83</td>
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<td>92.5</td>
<td>62.1</td>
<td>62.0</td>
<td>61.1</td>
<td>60.7</td>
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<td>22.29</td>
<td>12.83</td>
<td>14.52</td>
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<td>14.41</td>
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<td>14.97</td>
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<td>89.3</td>
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<td>14.11</td>
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<td>58.7</td>
<td>59.0</td>
<td>58.7</td>
<td>59.0</td>
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**Fig. 43b** Method I Ratios of Most Probable Fission to Alpha Ionizations and Tabulation of the Most Probable Fission Energies
<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>GAS</th>
<th>MOST PROBABLE ENERGY (MEV) LIGHT Ea Rl</th>
<th>HEAVY Ea Rhf</th>
<th>MOST PROBABLE ENERGY (MEV) AVERAGE PER GAS Ea Rlf</th>
<th>Ea Rhf</th>
<th>IONIZATION DEFECT RELATIVE TO THAT OF ARGON (MEV) ( \alpha \Delta f - x \Delta f )</th>
<th>EXTRA ENERGY IN MEV</th>
<th>NO. OF FISSIONS IN RUN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>92.9</td>
<td>60.7</td>
<td>92.7</td>
<td>60.8</td>
<td>0</td>
<td>105.4</td>
<td>18,600</td>
</tr>
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<td>2</td>
<td>A</td>
<td>92.5</td>
<td>59.2</td>
<td></td>
<td></td>
<td>+0.7±0.6</td>
<td>104.5</td>
<td>20,000</td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td>92.2</td>
<td>60.3</td>
<td></td>
<td></td>
<td>-3.2±0.6</td>
<td>104.7</td>
<td>24,400</td>
</tr>
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<td>A</td>
<td>93.1</td>
<td>62.8</td>
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<td></td>
<td>-1.1±0.0</td>
<td>105.7</td>
<td>28,500</td>
</tr>
<tr>
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<td>He</td>
<td>92.6</td>
<td>62.1</td>
<td>93.1</td>
<td>61.5</td>
<td>+0.4±0.6</td>
<td>106.2</td>
<td>30,300</td>
</tr>
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<td>He</td>
<td>93.5</td>
<td>60.9</td>
<td></td>
<td></td>
<td>0</td>
<td>106.2</td>
<td>28,700</td>
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<td>N₂</td>
<td>89.3</td>
<td>57.8</td>
<td>89.1</td>
<td>57.6</td>
<td>+0.4±0.6</td>
<td>101.8</td>
<td>20,000</td>
</tr>
<tr>
<td>8</td>
<td>N₂</td>
<td>88.8</td>
<td>57.3</td>
<td></td>
<td></td>
<td>-3.2±0.6</td>
<td>101.2</td>
<td>16,000</td>
</tr>
<tr>
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<td>Ne</td>
<td>92.0</td>
<td>59.2</td>
<td>92.3</td>
<td>59.4</td>
<td>-1.4±0.6</td>
<td>103.5</td>
<td>15,200</td>
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<td></td>
<td>0</td>
<td>105.2</td>
<td>17,000</td>
</tr>
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<td>CO₂</td>
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<td>55.6</td>
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<td>102.6</td>
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<td>CO₂</td>
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<td>101.9</td>
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<td>CO₂</td>
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<td>92.0</td>
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<td>-0.7±0.7</td>
<td>105.2</td>
<td>19,800</td>
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</table>

FIG. 43C METHOD 1 IONIZATION DEFECTS
<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>FISSION DISTRIBUTION</th>
<th>ALPHA DISTRIBUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RATIO OF MOST PROBABLE ENERGIES</td>
<td>RATIO LIGHT PEAK TO VALLEY</td>
</tr>
<tr>
<td>1 1.53</td>
<td>1.38</td>
<td>2.52</td>
</tr>
<tr>
<td>2 1.56</td>
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</tr>
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</tr>
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<td>13 1.56</td>
<td>1.51</td>
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</table>

FIG. 43d CHARACTERISTICS OF THE FISSION AND ALPHA DISTRIBUTION CURVES
<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>MOST PROBABLE IONIZATION IN MILLIVOLTS</th>
<th>RATIO OF MOST PROBABLE IONIZATIONS (xR)</th>
<th>MOST PROBABLE FISSION ENERGIES IN Mev.</th>
</tr>
</thead>
<tbody>
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<td>LIGHT</td>
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<td>19.35</td>
</tr>
<tr>
<td>3</td>
<td>458.7</td>
<td>309.0</td>
<td>19.43</td>
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<td>461.5</td>
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<tr>
<td>5</td>
<td>728.3</td>
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<td>478.0</td>
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FIG. 43e  METHOD II  MOST PROBABLE IONIZATIONS, RATIOS OF MOST PROBABLE FISSION TO ALPHA IONIZATIONS, AND MOST PROBABLE FISSION ENERGIES
<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>GAS</th>
<th>MOST PROBABLE ENERGY (MEV)</th>
<th>MOST PROBABLE ENERGY (MEV)</th>
<th>AVERAGE PER GAS</th>
<th>IONIZATION DEFECT RELATIVE TO THAT OF ARGON (MEV)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>LIGHT</td>
<td>HEAVY</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_a$ $R_{lf}$</td>
<td>$E_a$ $R_{hf}$</td>
<td>$E_a$ $R_{lf}$</td>
<td>$E_a$ $R_{hf}$</td>
</tr>
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<td>60.6</td>
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</tr>
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<td>A</td>
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<td>60.6</td>
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<td></td>
</tr>
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<td>88.5</td>
<td>58.1</td>
<td>88.7</td>
<td>58.4</td>
</tr>
<tr>
<td>7</td>
<td>N$_e$</td>
<td>91.2</td>
<td>60.2</td>
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<tr>
<td>8</td>
<td>N$_e$</td>
<td>92.2</td>
<td>60.9</td>
<td>91.7</td>
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<td>9</td>
<td>A$^+$ 3% CO$_2$</td>
<td>89.4</td>
<td>57.2</td>
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<td>57.0</td>
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<td>11</td>
<td>A$^+$ 5% N$_2$</td>
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<tr>
<td>12</td>
<td>A$^+$ 5% N$_2$</td>
<td>90.9</td>
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**FIG. 43f** METHOD II IONIZATION DEFECTS
<table>
<thead>
<tr>
<th>RUN</th>
<th>GAS</th>
<th>PRESS. mm H&lt;sub&gt;g&lt;/sub&gt;</th>
<th>MULT. ABOUT GRID WIRES</th>
<th>AVERAGE MOST PROBABLE IONIZATIONS IN MV. (CORRECTED FOR MULTIPLICATION)</th>
<th>eV</th>
<th>( x_{\text{He}^1} )</th>
<th>( x_{\text{I}^234} )</th>
<th>( x_{\text{f}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,6</td>
<td>A</td>
<td>400</td>
<td>( \approx 4% )</td>
<td>37.08 32.76 725.1 475.7</td>
<td>26.4</td>
<td>26.3</td>
<td>1.00</td>
<td>1.01</td>
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<tr>
<td>5</td>
<td>A</td>
<td>740</td>
<td>( \approx 1% )</td>
<td>37.36 32.84 723.8 473.3</td>
<td>26.4</td>
<td>26.2</td>
<td>1.01</td>
<td>1.02</td>
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<tr>
<td>3,4</td>
<td>He</td>
<td>2200</td>
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<td>23.60 20.80 462.0 305.3</td>
<td>42.7</td>
<td>41.4</td>
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<td>1.00</td>
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<tr>
<td>7,8</td>
<td>N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>425</td>
<td>0</td>
<td>26.89 23.66 503.1 325.4</td>
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<td>9,10</td>
<td>Ne</td>
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<td>27.17 23.71 523.5 337.6</td>
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<td>11,12</td>
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<td>38.15 33.39 71.70 444.2</td>
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<td>25.7</td>
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<td>1.11</td>
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<tr>
<td>13</td>
<td>A+5% N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>425</td>
<td>0</td>
<td>36.76 32.12 708.4 463.2</td>
<td>26.5</td>
<td>26.7</td>
<td>1.02</td>
<td>1.05</td>
</tr>
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**FIG. 44. SUMMARY AND COMPARISON OF VALUES OF \( w_\lambda \) FOR THE VARIOUS GASES**
DISCUSSION

Multiplication Effect

A discussion of the effect of multiplication of electrons about the grid wires of a gridded parallel-plate ionization chamber was not found in the literature. Wilkinson 6 mentioned that multiplication of electrons in gases would be most important for neon gas. Figs. 19 and 20 show that multiplication was observed in both purified neon and argon gases. Multiplication in neon and argon gases was observed at a calculated $X_{gc}/P$ of about 0.40 and 1.30, respectively. $X_{gc}$ was calculated assuming a uniform field between the grid and collector electrodes. However, the multiplication undoubtedly took place near the grid wires where the field was much stronger than that calculated. The $X_{gc}/P$ values, which signified the onset of multiplication, were consistent for different pressures of the same gas.

Fission and alpha distribution curves in neon gas were obtained at values of $X_{gc}$ which were lower than that observed for the threshold of multiplication. However, argon distribution curves at both 400 and 740 mm Hg were obtained with approximately 4 and 1 percent multiplication, respectively. It was necessary to operate $X_{gc}$ in the multiplication region for argon gas so that the
minimum ratio of fields was maintained for the largest values of $X_{gs}$ which were necessary to establish a reasonable saturation curve. As the multiplication became of the order of about 15 percent, the peak-to-valley ratio of the natural uranium alpha distribution was observed to become noticeably lower than that for the case of no multiplication. Part of this decrease was attributed to the increase of the low-frequency microphonics for increase of $V_{gc}$. However, the peak-to-valley ratio for 4 percent multiplication was not observed to be lowered. The addition of 1/3 percent of carbon dioxide into argon gas removed the multiplication which was present, but at the same time it introduced new effects which will be discussed later.

Multiplication curves in nitrogen, helium, and argon plus 5 percent nitrogen gases were relatively flat over the range of $X_{gc}$ from 470 to 1200 volts per centimeter.

The multiplication effect about the grid wires of a gridded parallel-plate ionization chamber might be used to increase the signal to noise level for amplified ionization pulses. In view of the loss of resolution for alpha pulses in the present chamber for multiplications of about 1.15, it is possible that the orientation of the particle path length is important. Gridded chambers which would employ larger multiplication factors than the present chamber and
would use particles collimated parallel to the source might
give a reasonable resolution for ionization pulses.

Saturation

The literature of the past ten years has contained many
experiments in which gridded parallel-plate ionization
chambers employing electron collection were used. Most of
the published papers mentioned that saturation was obtained,
but few of them gave specific data or indication of the
meaning. Methods were developed in the present experiment
so that relatively small changes in pulse height of alpha
particles were detected reasonably accurately and in a short
time. Thus, accurate determinations of pulse height as a
function of chamber conditions were possible, and saturation
curves in the various gases were obtained which showed pulse
height changes in percent as a function of the source elec-
trode voltage. All ionization chamber gases used in this
experiment were purified except those which were a mixture
of two gases.

The ranges of saturation curves were limited on the
upper end by the breakdown characteristics of the gas and the
chamber geometry or by the maximum voltage (≈5000 volts)
which could be safely applied to the source electrode.
Curves for neon gas were particularly limited by the former, and those in argon gas at 400 and 740 mm Hg were definitely restricted. The region of relatively constant pulse height for alpha particles in argon gas at 400 mm Hg (Fig. 21) was limited to a narrow range by voltage breakdown at the upper end and by rise time and recombination effects at the lower. For argon gas at 740 mm Hg (Fig. 22) the effect of rise time was diminished while a somewhat higher voltage could be applied before breakdown, and the flat portion of the alpha particle saturation curve appeared to be broader.

Alpha particle saturation curves for helium and neon were considered adequate, and those for nitrogen were very good. No significant decrease of pulse height in nitrogen gas was observed for $X_{gs}/P$ values from 1.4 to 0.6. The nominally flat portion of the saturation curves for helium and neon gases actually exhibited a small positive slope. For example, in neon gas (Fig. 27) a change of $X_{gs}$ from 0.06 to 0.12 resulted in a relatively linear pulse height increase of about 1 percent. Since both helium and neon gases have relatively higher positive ion mobilities than argon or nitrogen, a part of the changing pulse height can be attributed to the incomplete screening of the collector electrode from the source volume by the grid. Also the
values of $X_{gs}/P$ are relatively low in helium and neon and the gases may not be completely saturated.

Fission saturation curves (Fig. 36) were obtained, in general, on the same films as the main fission distributions which were used in the ionization defect calculations. At least two smaller distribution curves were taken before or after the first main fission distribution for a particular gas, and the main fission distribution was used as one of the points on the saturation curve. Values of $V_{gs}$ for the additional points were selected to show the general shape of the saturation curve in the vicinity of $V_{gs}$ for the main fission run. The median calculation of Method 2 was used to determine the most probable pulse heights, except for one change. Division of the distribution into the light and heavy fission peaks was carried out for the main fission distribution as usual, but the median values for the other distributions were located by using the same relative ionization limits for the two peaks as for the main distribution.

If the lack of saturation was more severe for fission fragments than for alpha particles in the same gas, the calculated most probable fission energies would be smaller than they should be. However, the fission saturation curves in helium, neon, and argon gases were very similar to those
for the alpha particles except at the lower values of $X_{gs}$. Fission and alpha saturation curves in nitrogen gas were not significantly different for values of $X_{gs}$ from 1.4 to 0.5.

Many of the gridded parallel-plate ionization chambers used in recent years have employed argon gas plus small percentages of carbon dioxide gas. This gas mixture was investigated and used in the present experiment to obtain a comparison with the pure argon gas.

Rise times of alpha particle pulses in mixtures of argon and carbon dioxide gases were observed to be considerably faster than those for the rare gases or nitrogen. Rise times in a gridded chamber using 3 percent carbon dioxide at pressures from 425 mm Hg and higher were observed to be 2 microseconds or less for $X_{gs}$ values greater than 100 volts per centimeter. Mixtures of 1/3 percent of carbon dioxide in argon gas at 1 atmosphere and higher showed rise times which were only slightly higher than those for the 3 percent mixture at the same values of $X_{gs}$. Rise times in the 1/3 percent mixture at 425 mm Hg were observed to be about 1/4 microseconds for $X_{gs}$ of about 100 volts per centimeter.

The addition of small percentages of carbon dioxide gas to argon gas gave rise to some peculiar characteristics which are indicated by the saturation curves of Figs. 28-30.
The first indication of the peculiar characteristics was observed for a 3 percent mixture at 425 mm Hg. The saturation curve is shown in Fig. 28, and it was observed that the pulse height quickly came to a maximum and then decreased as $X_{gs}$ was increased further. Such a behavior was contrary to the previously published experimental work with this gas mixture which was believed to give excellent saturation curves for alpha particles, even at very low values of $X_{gs}$. The saturation curves of the 3 percent mixture were investigated as a function of pressure and they are given in Fig. 28. Each of these curves was obtained using the same set of electrode voltages. A relatively drastic change in the shape of the saturation curves was observed to take place between gas pressures of 425 and 740 mm Hg. The curve at 740 mm Hg was very flat over the range of $X_{gs}$ from 125 to 625 volts per centimeter, in contrast to that at 425 mm Hg. At the increased pressures of 1500 and 2200 mm Hg the pulse heights increased slowly as $X_{gs}$ was increased. It would appear that there were several additional effects present in the mixture, at least one of which was pressure dependent. The flat alpha particle saturation curves at pressures in the neighborhood of 700 mm Hg may arise from the combination of several effects.

Fission fragment saturation curves for 3 percent
mixtures of carbon dioxide in argon gas have been published by Brunton and Hanna and have been obtained in the present work (Fig. 36). Both curves are characterized by a relatively high value of $X_{gs}$ corresponding to saturation. This high value of $X_{gs}$ for fission fragments was in sharp contrast to that for alpha particles under the same chamber conditions. Differences between the fission and alpha saturation curves in the pure gases and in argon plus 5 percent nitrogen were not nearly as marked. This larger difference between the fission and alpha saturation curves in argon plus 3 percent carbon dioxide suggested that the density of ionization had a larger effect in this mixture.

Fig. 29 shows the ratio of fields curves for argon plus 3 percent of carbon dioxide at pressures of 425 and 740 mm Hg. Because of the anomalous effects, the values of $Z_m$ as a function of $X_{gc}$ for 425 mm Hg were found to be inconsistent between themselves and to be higher than those for the higher pressures. $Z_m$ values at the higher pressures (Fig. 30) were quite consistent.

The saturation properties of pure carbon dioxide gas were investigated briefly, and Fig. 31 shows a saturation curve. Saturation properties of carbon dioxide for electron collection were not regarded as good.

The alpha particle saturation characteristics of
mixtures of carbon dioxide and argon gases were investigated further by observing the characteristics of argon plus 1/3 percent of carbon dioxide gas at various pressures. The saturation curves and values of $Z_m$ are shown in Fig. 32. Voltages on the chamber electrodes were the same for the curves at 2200 and 1500 mm Hg, but the grid voltages were changed for the curves at 740 and 425 mm Hg. Points at which the values of the ratio of fields (1.65) would cause the curves at 740 and 425 mm Hg to come down are indicated. It is evident that the saturation curves at these two pressures decreased prematurely and had the same decreasing characteristics as the curve for the 3 percent mixture at 425 mm Hg. For the 1/3 percent mixture the saturation curve for 1500 mm Hg appears to have the best characteristics for alpha particles, and the curve at 2200 mm Hg has the pulse height rising slowly with the increase of $X_{gs}$.

Comparison of the two sets of saturation curves for argon gas plus carbon dioxide mixtures indicated that for a given mixture there was a limited range of pressure which resulted in excellent saturation curves. However, a question might be raised regarding the meaning of a saturation curve under such limitations.

Fig. 19 shows the multiplication curves for alpha
particles in purified argon at various pressures, and the
curve for argon at 425 mm Hg is increasing rapidly over
the range of \( V_{gc} \) which was observed. However, when \( 1/3 \) percent of carbon dioxide was added to the argon gas, the
multiplication curve in the same range of \( V_{gc} \) decreased
nearly as rapidly as the curve had previously increased for
pure argon gas. Higher pressures of the argon and carbon
dioxide gas mixtures and increased percentage of carbon
dioxide in the argon gas caused the multiplication curves
to fall off less rapidly. The multiplication curve in pure
carbon dioxide had a slight tendency to rise with increased \( V_{gc} \).

The difference in saturation characteristics between
alpha and fission particles in a mixture of argon and carbon
dioxide gases apparently must be explained in terms of the
differences in the densities of the ionizations. If a large
number of carbon dioxide molecules were broken up into their
components, i.e. oxygen and carbon monoxide, by the processes
which stopped the energetic primary particle, it would be
possible to visualize the difference in terms of electron
attachment. Since oxygen, at least, has a large electron
attachment coefficient, some of the electrons could be
attached before they were removed from the volume of the
particle path. Such an effect would, of course, be more
prominent for fission fragments than for the alpha particles.

In mixtures of argon and carbon dioxide gases the decreasing characteristics of the alpha particle saturation curves for increasing \( X_{gs} \) might be explained by an impurity in the mixture or by some type of inelastic collision between the free electrons and the molecules of carbon dioxide as the electrons move through the gas to the collector electrode. One might visualize a resonant attachment reaction between the electron and the carbon dioxide molecule or a resonant molecular reaction which leads to a break-up of the molecule and to electron attachment to one of the components. Also since the density of ionization for a fission fragment is initially a factor of ten larger than that of an alpha particle, the same ratio will, in general, prevail until the electrons are collected (neglecting the differences in the repulsions between the electrons). The difference in saturation curves between fission and alpha particles might be accounted for using this inelastic collision concept between electrons and carbon dioxide molecules.

At the present time it appears that there is not enough information available to justify making predictions regarding the mechanism of the effects which are in evidence. It would be desirable to have more complete data on alpha saturation
curves for a wide range of argon plus carbon dioxide mixtures and at a number of different pressures for each mixture. A corresponding series of fission saturation curves for different mixture pressures and for varying percentages of carbon dioxide might be valuable. Also a study of mixtures of other selected gases with carbon dioxide would be of interest, as well as studies of mixtures of other molecular gases with argon gas. The use of a two electrode parallel-plate ionization chamber (ungridded chamber) having parallel-plates with guard rings, particles collimated parallel to the plates, provision for high electric fields between the plates, and a system for insuring the purity of the gases would bring the problem closer to the fundamentals which are involved.

In the present work a gas mixture of argon plus 5 percent nitrogen was used to measure the most probable energies of fission fragments and alpha particles. Addition of the nitrogen to the argon was expected to lower the electron temperature of the gas, in the same manner as carbon dioxide, and thus to increase the drift velocity in the mixture over that of purified argon without giving rise to peculiar saturation effects. Rise times of alpha particles pulses were observed for a 5 percent mixture at a pressure of 425 mm Hg, and they were found to be 2 microseconds or
less for $X_{gs}$ values from 230 to 560 volts per centimeter. Alpha saturation curves for this mixture are shown in Fig. 33, and they are observed to have a constant pulse height over a wide range of $X_{gs}$. Also the fission saturation curve for this mixture (Fig. 36) was found to decrease only slightly faster than the alpha curve, as $X_{gs}$ was decreased from the maximum value.

Although the data have not been presented on a graph, some work was done on a mixture of argon plus 1 percent of nitrogen gas at 425 mm Hg. Pulse rise times were again observed to be much faster than those of pure argon gas. For changes of $X_{gs}$ from 140 to 600 volts per centimeter, the rise times decreased from 3 microseconds to less than 1. The alpha saturation curves were similar to those for argon plus 5 percent of nitrogen.

From the evidence which has been obtained in the present work, characteristics of argon plus carbon dioxide mixtures are not well understood. Since the addition of carbon dioxide to argon gas is usually done only to increase the drift velocity of electrons in the mixture, it would appear that the addition of nitrogen gas instead would give very nearly as high a drift velocity to the mixture without introducing other effects which are not understood. The results of the present work do not permit a close comparison
of the drift velocities for addition of carbon dioxide and nitrogen to argon gas. However, the drift velocities for each type of mixture are about ten times faster than those for the pure argon gas. Drift velocities for carbon dioxide mixtures appear to be somewhat faster than those for the nitrogen mixtures.

In view of the present understanding of what constitutes saturation, the saturation curves for alpha particles and fission fragments are believed to be very good for nitrogen gas and argon plus 5 percent nitrogen and good for argon, helium, neon, and argon plus 3 percent carbon dioxide.

Ratio of Fields

For the geometry of the present chamber the minimum ratio of fields for complete electron collection was calculated to be about 1.30. This theoretical calculation assumed that the electrons followed the electric field lines exactly.

Experimental observations showed that $aZ_m$ (2.2) was much larger than the theoretical value. Further investigation of the ratio of fields for helium gas showed the observed ratio of fields to be considerably lower ($\approx 1.7$) than that for argon gas. The effect of electron diffusion
on the ratio of fields was then investigated.

Wilkinson arrived at an equation which relates the electron temperature and electric field strength in a gas to the mean displacement from the plane of the center of gravity of the ionization divided by the distance the center of gravity travels along the field. The ratio of mean displacement to distance travelled is an indication of the importance of diffusion and is designated by $D$ in Fig. 35. $D$ is proportional to the square root of the ratio of electron temperature to $X_{gs}$. The values of $X_{gs}$ were calculated assuming uniform fields between the source and grid electrodes. These values of $X_{gs}$ were in error because the source electrode was not plane. However, the field in the vicinity of the grid was not expected to be different from the calculated value of $X_{gs}$ by the amount necessary to account for the difference in the observed and theoretical values of the ratio of fields. Further, it was noted that the value of $X_{gs}$ which was used in the calculation of $D$ would in all probability be much smaller in absolute magnitude than that which actually existed in the close proximity of the grid wires where the electrons diffused away from the electric field. However, the calculated values of $X_{gs}$ were proportional to the electric fields nearer the grid wires. Values of $\eta$ for the calculation of $D$ were obtained from
Fig. 34. Electron temperatures for carbon dioxide gas and for mixtures of gases were not available. Comparisons of the changes in the calculated values of \( D \) with the changes in the observed value of \( \frac{x}{Z_m} \) for each of the gas conditions show a good correlation. As the magnitude of the electron diffusion is increased, the minimum ratio of fields required for complete electron collection is increased.

Fig. 35 shows the correlation between electron diffusion and \( \frac{x}{Z_m} \) where \( X_{gs} \) was assumed to be the participating electric field. However, the correlation using \( X_{ge} \) instead of \( X_{gs} \) was found to be reasonably good also. Thus, there is some question as to which electric field, or what combination of them, should be used in the calculation of \( D \).

From Fig. 35 it was observed that \( \frac{x}{Z_m} \) for argon and neon gases increased significantly as the pressure was decreased. This trend was accounted for in either argon or neon gas by comparing two ratio of fields curves which were taken at different pressures but which had approximately the same \( \frac{x_{gs}}{P} \) value for the minimum ratio of fields. In this event the electron temperatures at the two pressures remained about the same, and the increase in \( \frac{x}{Z_m} \) was probably due to the decrease in the value of \( X_{gs} \), and consequently increase in \( D \).

Since electron temperature data for the mixtures of
argon plus carbon dioxide or nitrogen gases and for pure carbon dioxide were not available, $D$ was not calculated for these cases. However, the electron temperature for pure carbon dioxide was probably of the order of about three for the values of $X_{gs}/P$ which were used. In this case $D$ would be close to zero and $Z_m$ would be at its lowest value. This value of 1.45 for $Z_m$ in carbon dioxide gas was still above the theoretical minimum of 1.30, but the remaining difference was attributed to the deviation of the electric field from that calculated assuming parallel plates. A value for $Z_m$ of about 1.5 for argon plus 3 percent carbon dioxide indicated that the electron temperature of this mixture was almost as low as that for pure carbon dioxide. Also the lowered values of $Z_m$ for argon plus 1/3 and 5 percent of carbon dioxide and nitrogen, respectively, indicated that the electron temperature was considerably below that for pure argon gas. The lowering of the electron temperature by the addition of small percentages of carbon dioxide and nitrogen gases to argon was further substantiated by observing that the drift velocities in the gas mixtures became higher than those for pure argon.

Although values of $Z_m$ for neon gas at 840 mm Hg were observed to be higher than for argon, the values of $D$ for neon were approximately the same as those for argon. This
discrepancy perhaps arises from the inaccuracies in the
electron temperature curves for the low values of $X_g^*/P$
which were in effect for neon gas. The discrepancy between
the $D$ values in nitrogen and helium gases, which have
approximately the same value of $Z_m$, may be attributable
to the same type of inaccuracy in the helium curve.

Ionization Defects

The characteristics of each of the fission and alpha
distribution curves are tabulated in Fig. 143d, and they are
reasonably consistent between each run. Few data concern­
ing the characteristics of the fission fragment distribution
for fission of $^{238}\text{U}$ were given in the literature. There
was no apparent reason why this fission distribution should
differ significantly from the fission distributions of other
fissionable isotopes which can be initiated by slow neutrons.
Comparison of the characteristics of the present distribution
curves with those of others gave good agreement except
for a larger width at half-maximum of the fission peaks for
the present experiment. Literature values of the width at
half-maximum for the light and heavy fission fragment peaks
averaged about 14 and 22 Mev, respectively. These widths
appeared to roughly correlate with the source thickness and
the degree of collimation. In the present experiment the
widths at half-maximum averaged about 17.3 and 29.6 Mev. The poorer resolution for the fission peaks was probably due to the distribution of energy loss in the source. The source was relatively thick (50 micrograms per square centimeter) and the collimation was not severe (particles emitted at angles up to 77 degrees from the normal were allowed).

For each fission distribution curve and accompanying calibration curves, it was necessary to record data over an average period of about eight hours. At intervals during this period the gain of the amplifier system was checked in the following way. The standard pulse generator was connected to the ionization chamber source electrode in the usual way, and the input pulse magnitude was adjusted to produce an output pulse from the push-pull amplifier of approximately 250 volts. The bias voltages on the electronic analyzer were set so that the calibrator pulse fell between two of the analyzer channels. Under these conditions the two selected channels would give nearly equal counts over a short observational period. At two hour intervals during most of the fission runs, a constant calibrator pulse height was placed on the source electrode, and the gain of the amplifiers was checked by observing the counting rates of the two adjacent channels of the electronic analyzer. Changes in the calibrator pulse height of 2/10 percent
were large enough to cause one of the channels to almost stop counting and the other to count correspondingly faster. It was believed that changes of 1/10 percent in the gain were detectable providing that the electronic channel analyzer was comparably stable over these periods of time. In many cases the amplifier gains were not found to have drifted by more than plus or minus 1/10 percent over the eight hour period. However, in a couple of cases the gain was detected to have drifted as much as 2/10 percent, and this was the error which has been established for the gain variation.

The calibration procedure for both fission and alpha distributions was described previously. There were ten equal steps available across the face of the oscillograph, but the usual procedure was to use the top seven and eight steps for the alpha and the fission calibrations, respectively. In all fission runs at least two calibration curves were obtained, one before and one after the main fission run. An average calibration distribution curve was obtained by combining the counts in the corresponding channels of the individual calibration distributions and using this to locate the calibration points. Figs. 37 and 38 show only three and six points of the alpha and fission calibrations, respectively. A least square fit of a straight line using
at least six points was calculated for each of the thirteen alpha and fission distributions. The calibration equations were obtained in terms of the relative ionization and the calibrator voltage in millivolts. When the most probable relative ionizations of the alpha and fission distributions were obtained by Methods 1 and 2, which were previously described, the values were substituted into the calibration equations and the most probable ionizations were obtained in terms of millivolts. Values of the most probable ionizations for the alpha and fission distributions using Method 1 are given in Fig. 43a, and those for fission fragments using Method 2 are given in Fig. 43b.

The two methods for determining the most probable ionizations for both the alpha and fission distributions were described previously. Both of these methods assumed that data for the distribution curves were available in a form showing the number of events per unit pulse height interval. A comparison will now be made between the two methods. The weakest link in the chain of procedures for Method 1 was the location of the sides of the distribution peaks. The shape of the cap of the distribution peak was not critical since the relative ionization corresponding to the intersection of the median line (between the two sides of the peak) and the cap was a slowly varying function
of the cap shape. After the sides of each peak were located, the remaining steps were geometrical and mathematical. Method 2 was developed to make the process less dependent on the interpretation of the fission distribution shape. In this procedure it was necessary to graph only the upper side of the light fission fragment peak and to draw a straight line through the inflection point to the axis of zero counts. Since this side was relatively steeper than the others, the slopes of the lines making the best fit to the points about the inflection point were limited to a narrow range of values. After obtaining the value of the intercept, a mathematical procedure was used to obtain the most probable fission ionization.

Method 2 was somewhat arbitrary in the designation of the most probable pulse heights. However, assuming the general shape of the fission distribution curves did not vary significantly, the method designated a consistent peak position which was not very different from the most probable pulse height.

Using Methods 1 and 2 the most probable alpha particle and fission fragment ionizations were obtained (see Figs. 43a and 43e). The only difference in the two methods for obtaining the most probable light and heavy fission fragment energies for each run was the manner in
which the most probable fission ionizations were obtained from the distribution curves. For each run it was possible to obtain two values for the most probable light fragment energy and two for the most probable heavy. This was done by comparing each of the most probable fission ionizations to the two most probable alpha particle ionizations to obtain four values of $R$ (see Figs. 43b and 43e). Those values of $R$ which were obtained by comparing the fission ionizations to that of the $\text{U}^{238}$ alpha particle were multiplied by 4.76 Mev, and those compared to the $\text{U}^{238}$ alpha particle were multiplied by 4.18 Mev. The resulting four values of the most probable fission energies (see Figs. 43b and 43e), two for the light fragment and two for the heavy, were averaged for the run (see Figs. 43c and 43f). The average values of the most probable light and heavy fission fragment energies for a gas (see Fig. 43c and 43f) were then obtained. The quantity $(a\Delta f - x\Delta f)$ was calculated by subtracting the average most probable fission fragment energy for argon gas from that for a gas $x$. The results of the calculations of Method 1 and Method 2 are tabulated in Figs. 43c and 43f, respectively. The extrapolated ionizations (Fig. 43a) which were used in Method 2 were converted to energies (Fig. 43c) in the same manner as the most probable fission ionizations. Comparison of the
average extrapolated energies between gases was also an indication of the changes in ionization defects of fission fragments between gases.

None of the fission energies which were obtained in this experiment have been corrected for losses of energies in the uranium source or in the collimator. Since the same source and collimator were used throughout the experiment, the energy losses were practically constant for all of the gases and gas mixtures which were used.

The results of the calculations to determine the difference between the ionization defect of argon gas and those of other gases and gas mixtures will now be discussed.

When the average most probable light fragment energy in argon gas was subtracted from that in helium, the resulting difference in ionization defects was found to be .4 ± .6 and .5 ± .4 Mev for Methods 1 and 2, respectively. The corresponding differences for the heavy fragment were .7 ± .6 and 1.2 ± .4 Mev. From these values one can say that the light fragment energy in helium gas was close to being significantly higher than that for the argon, and that the heavy fragment energy appeared to be significantly higher. The average extrapolated energies of argon and helium gases were 105.1 ± .5 and 106.2 ± .5 Mev, respectively. The difference in the ionization defects for the
fission fragments corresponding to the extrapolated ionizations was 1.1 ± 0.7 Mev. Again this value was significantly above zero. In view of the preceding results the differences in the ionization defects between argon and helium gases were estimated at 0.5 and 1 Mev for the most probable light and heavy fragments, respectively.

The magnitudes of the ionization defects in helium gas were not expected to be so close to those of argon, which were given previously as 5.7 and 6.7 Mev for the most probable light and heavy fission fragments, respectively. The arguments against such a large defect in helium were based on the mechanics of energy transfer to the helium atom in an elastic collision with a fission fragment. Because the mass of the helium atom is small compared to the argon atom, which in turn is less than the mass of the average fission fragment, it was expected that more energy would be transferred to the recoil argon atom than to the helium. The heavier recoil argon gas atoms were expected to have a reduced ionization efficiency over that for the recoil helium atoms. On this basis it was expected that the ionization defects in helium gas would be from 3 to 5 Mev smaller than those in argon. The influence of the systematic errors (which are further discussed in the error analysis) on the difference of the ionization defects in argon and helium
gases will now be discussed. Only the errors relative to the saturation curves and to the differential rise time effect of the alpha and fission pulses were deemed important to this analysis.

If there were a lack of saturation in either the argon or helium gases, it would be expected to be worse for the fission fragments than for the alpha particles, because of the difference in ionization densities. Thus lack of saturation in a gas would cause the fission energies to be lowered. If the degree of saturation in argon were higher or lower than that in the helium, the difference in the ionization defects would become smaller (and even negative) or larger, respectively. From the experimental work it appeared that if there were a difference in the degree of saturation between the two gases, the saturation in argon gas was more complete than that in helium. A correction for this effect would tend to increase the observed difference in the ionization defects between the two gases.

The differential rise time effect was discussed in a previous section, Determination of Saturation Curves, where it was shown that the effect would increase the ratios of the fission to alpha ionizations and thus increase the fission energies. Further the effect was estimated to have increased the fission energies in argon gas by no more than
1/2 percent. Since the rise times of the ionization pulses in helium gas were somewhat shorter than those in argon (see Fig. 5), the corresponding increase in the helium fission energies would not be quite as large. When the amplifier, alpha particle, and fission fragment rise times were taken as 30, 10, and 6 microseconds, respectively, the differential rise time effect increased the helium fission energies by about 1/4 percent. Thus the differential rise time effects between the two gases caused a relative difference of about 1/4 percent. The correction for this effect would be in a direction to increase the observed differences in the fission ionization defects between helium and argon gases. It would appear that, providing a correction were made for the saturation and rise time effects, the ionization defect differences of .5 and 1 Mev for the light and heavy fragments, respectively, would not be increased by more than about .5 Mev.

The inability to detect larger differences between the ionization defects in helium and argon gases might be explained in at least three ways. First, there is some question about the magnitudes of the charges of fission fragments between different gases, particularly at the high pressures which were used. Second, there is a double-ionization effect which is known to exist in helium gas, at
least for alpha particles. Third, the number of helium metastable states may vary percentagewise between alpha and fission particles.

First, Lassen has investigated the effective charges of fission fragments which were passing through various gases at pressures of the order of a few mm Hg. He observed that the effective charges of the most probable light and heavy fragments were lower in helium gas than in argon. If such an effect could be extrapolated to the much higher pressures which were used in the present experiment, the high value of the ionization defect of helium gas might be explained by the reduction in the ionization probability without particularly changing the atomic collision probability. Lassen's work showed that fission fragments in hydrogen gas at low pressures had about the same effective charge as in argon. In spite of the long extrapolation of charge effects of fission fragments as a function of gas pressure, it was hoped that the measurement of the ionization defect of fission fragments in hydrogen gas would provide some information regarding a dependence of the ionization defect on the effective charge.

Second, another possible explanation of the high value of the ionization defect in helium gas is that recoiling helium atoms produce double ionization in their own gas. Since the ejection of two electrons from a helium atom requires about 1.6 times as much energy as ejecting two electrons from two helium atoms, the energy per ion pair would be increased in those regions where the double ionization was produced. Wilkins found that near the end of the range of alpha particles stopped in helium gas, the positive ions consisted of about 10 percent doubly ionized atoms. He further found that the number of double ionizations increased to a maximum when the ionizing power of the alpha particles was a maximum and that no appreciable double ionizations were found in air or hydrogen. A high rate of production of the doubly ionized helium atoms in the stopping processes for fission fragments could account for a relatively higher energy per ion pair. The measurement of the ionization defects of fission fragments in hydrogen gas would also eliminate this effect, if it were responsible for the high defect in helium gas.

Third, if the number of the metastable states in helium gas were higher percentagewise for fission fragments than

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for alpha particles, the helium fission energies would be lower and the fission ionization defect for helium gas would be increased. It is not unreasonable to surmise that there might be additional excitation in the end of the fission fragment path over that of alpha particles. This effect is subject to check by adding a few tenths percent of argon gas to the helium. Since the helium metastable state has more energy than the ionization potential of the argon gas, the metastable states will decay by ionizing argon atoms.

An attempt was made to use hydrogen gas in the present ionization chamber, but the saturation characteristics were extremely poor for the $X_{gs}/P$ values which were available. After purification of the gas the alpha particle pulses were scarcely higher than the noise level for the maximum $X_{gs}/P$ value of about four-tenths.

Differences in the ionization defects between argon and neon gases were not found to be significant when the corrections for saturation and differential rise time effects in argon gas were applied. Negative values for the most probable light fragment were $0.4 \pm 0.6$ and $0.5 \pm 0.4$ MeV for Methods 1 and 2, respectively, and those for the heavy fragment were $1.4 \pm 0.6$ and $1.4 \pm 0.4$ MeV, respectively. The averages of the values for the light and heavy fragments
were taken as 0.5 and 0.9 Mev, respectively. The application of the rise time correction in argon gas would decrease the above values by about 0.4 Mev, since the rise times in neon gas were significantly faster than those in argon and the saturation characteristics in argon and neon were somewhat similar. Remaining differences in the ionization defects were not deemed significant for the present experiment. Comparison of the average extrapolated energies between the two gases showed an uncorrected difference of 0.7 Mev and was another indication that the differences in defects were small.

When the average most probable light fragment energy in argon gas was subtracted from that in nitrogen gas to obtain the difference in the ionization defects, the value was found to be negative and equal to 3.6 ± 0.6 and 3.5 ± 0.4 Mev for Methods 1 and 2, respectively. The corresponding values for the heavy fragment were also negative and equal to 3.2 ± 0.6 and 2.5 ± 0.4 Mev, respectively. The negative values indicated that the ionization defects for the most probable light and heavy fragments in nitrogen gas were larger than those in the argon by about 3.5 and 2.8 Mev, respectively. Comparison of the extrapolated energies in the two gases showed the value in argon gas to be 3.6 Mev larger than that in nitrogen. Nitrogen gas had very good
saturation characteristics and the alpha pulse rise times in nitrogen were considerably faster than those in argon. Correction for the differential rise time effect in argon would decrease the observed differences in the ionization defects by about 0.5 Mev, and the saturation correction would slightly increase the observed value. The combined corrections would result in less than a 0.5 Mev decrease in the observed differences.

Since the mass of a nitrogen atom is smaller than that of an argon atom, the additional ionization defect over that of the argon gas could not be explained on the basis of the elastic collisions between the fission fragments and the nitrogen atoms. However, it was observed that the molecular binding energy of the nitrogen molecule was of the order of 7 electron volts. It was then postulated that a larger portion of the fission fragment energy was being diverted from ionizing processes to radiation through the breaking of the molecular bonds of the nitrogen molecule. For molecular gases the ionization defect might be broken up into atomic and molecular components, hereafter called the atomic and the molecular defects. It might be expected that

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for the molecular gases the molecular defect would be particularly large for the recoil gas atoms and for the fission fragments at low velocities, in much the same manner as the atomic defect.

When the average most probable fission energies of argon gas were subtracted from those of argon plus 5 percent nitrogen, negative values for the differences in ionization defects were obtained. For the most probable light fragment Methods 1 and 2 gave $0.7 \pm 0.7$ and $1.3 \pm 0.5$, respectively, and for the heavy they gave $1.9 \pm 0.8$ and $1.1 \pm 0.5$, respectively. The average differences in the ionization defects for the most probable light and heavy fragments were taken to be $1.3$ and $1$ Mev, respectively. Again the saturation characteristics of the gas mixture were very good, and the pulse rise times were a factor of ten shorter than those in argon. Thus the saturation and differential rise time corrections would be practically the same as for the comparison of argon and nitrogen gases, or less than $0.5$ Mev. Since only one run was taken in the mixture, these corrections appeared to place the difference between the ionization defects in the close-to-significant class. However, the extrapolated energy comparison indicated that the difference in ionization defects was nearly zero. On the basis of the large ionization defect in nitrogen gas,
the mixture of argon plus 5 percent nitrogen might be expected to have at least a slightly larger defect than the argon gas.

The differences in the ionization defects between argon gas and argon plus 3 percent carbon dioxide were investigated. Both Methods 1 and 2 gave negative values for the light fragment, $3.1 \pm 0.6$ and $2.9 \pm 0.4$ Mev, respectively, and for the heavy fragment, $5.2 \pm 0.6$ and $3.8 \pm 0.4$ Mev, respectively. These differences in ionization defects for the light and heavy fragments were among the largest found in the present experiment, and they were placed at 3 and 4.5 Mev, respectively. The saturation characteristics were good and the alpha pulse rise times were a factor of ten less than those of argon so that only corrections for the argon gas were significant. The correction has been estimated previously and it decreased the differences in ionization defects by less than 0.5 Mev. The extrapolated energies differed about 2.8 Mev between the argon and the argon mixture and in the same direction as Methods 1 and 2.

The differences in the defects between argon and argon plus carbon dioxide were not surprising, perhaps, in view of the defects which were found in nitrogen gas. However, the large magnitudes of the defects in only a 3 percent
mixture were surprising. Since the carbon dioxide molecule is more complex than nitrogen, the larger defect might indicate that the molecular defect for carbon dioxide gas is much more important than that in nitrogen.

The presence of a relatively larger fission fragment ionization defect in argon plus 3 percent carbon dioxide over that of argon gas produces a basis for speculation about the meaning of the fission fragment ionization defect which has been discussed in the literature and which has been attributed to the argon gas. In a previous section, Introduction, the evidence for a fission ionization defect in argon gas was indicated by comparisons of double chamber ionization data with radiochemical data, with velocity distribution data, and with calorimetric data. The double chamber ionization experiments \(^{13}\) which were usually referred to in these comparisons used mixtures of argon plus 2 or 3 percent of carbon dioxide gas. On the basis of the present results it would appear that the ionization defect for fission fragments in argon gas should be decreased for the most probable light and heavy fission fragments by something like 2.5 and 4 Mev, respectively. The comparison of the velocity distribution of fission fragments with the velocity distribution which was inferred from double chamber ionization data gave ionization defects of 5.7 and
6.7 Mev for the most probable light and heavy fission fragments. If these quantities were decreased, as indicated above, the ionization defect in argon gas would be 2.2 and 2.7 Mev for the light and heavy fragments, respectively. These values would be in somewhat better agreement with those of Knipp and Ling \(^2\) who calculated the defects in argon to be 2.5 and 4.2 Mev for the light and heavy fragments, respectively.

The larger fission ionization defect in argon plus 3 percent carbon dioxide over that of argon gas suggested a possible explanation of the differences between the measured values of the alpha ionization defect in argon gas. This discrepancy in the value of \(a_{\text{W}}^{\#}\) for alpha particles at low energies was discussed in a previous section, Introduction. In the discussion it was indicated that the measurements of Jesse et al. \(^9\) were not confirmed by Cranshaw and Harvey \(^8\), Rhodes et al. \(^10\), Hanna \(^3\), and Brunton and Hanna \(^13\). The argon gas used in the last three experiments contained 5, 2, and 3 percent of carbon dioxide, respectively, and Hanna \(^3\) also used argon plus 2 percent boron trifluoride. The molecular defect of the boron trifluoride molecule may be comparable with that of the carbon dioxide. Jesse et al. used argon gas of spectroscopic purity for most of the measurements and argon plus
.1 percent boron trifluoride for one of the measurements. The .1 percent boron trifluoride might not be a large enough quantity to show an appreciable molecular defect. The work of Cranshaw and Harvey was done with tank argon which was 99.8 percent pure. However, in this case the energy per ion pair which was measured for polonium alpha particles in argon gas was considerably higher (28.3 electron volts per ion pair) than that obtained by Jesse et al. 27 and by Sharpe 36 (26.4 electron volts per ion pair). Because of the uncertain purity of the ionization chamber gas used by Cranshaw and Harvey and of the high value of the energy per ion pair of alpha particles in argon gas, it appeared that this experiment would not carry as much weight as the others. It would then seem possible that the alpha particle ionization defect could be explained by a molecular defect in the mixtures of argon and molecular gases.

If the relative ionizations of an alpha particle stopped in various gases were obtained on the same scale, as in the present case, the products of the relative ionizations and the average energies per ion pair in the gases should be a

constant. The energy per ion pair for alpha particles in nitrogen gas, $nW\alpha$, was taken to be 36.4 from the work of Sharpe 36, and the $x^W\alpha$ values for the other gases were calculated relative to that of nitrogen. Nitrogen was taken as the base for the calculation because the literature values were quite consistent, there was no multiplication present, and the gas characteristics appeared to be relatively insensitive to small impurities 26. The calculated values of $x^W\alpha$ relative to that of nitrogen are presented in Fig. 44. It was observed that the calculated and literature values 27,36 compared quite favorably. As far as it is known, these high values for $he^W\alpha$ and $ne^W\alpha$ using electron collection had not been observed before. Jesse et al. 27 first observed the higher values using total ion collection and very pure gases. The high values of $W\alpha$ for helium and neon gases in the present experiment were good evidence for the purity of these gases and for the effective action of the purifier in the other gases.

The last two columns of Fig. 44 were calculated to show the percentage increase in $x^W\alpha$ compared to $he^W\alpha$.

As a result of the experience with the present experiment, it is possible to make suggestions of changes which would improve the accuracy of the present measurements or which would, perhaps, foresee some of the
difficulties in the design of an ionization chamber using electron collection for other measurements. (1) The differential rise time effect between alpha particles and fission fragments in those gases with relatively slow drift velocities could be experimentally decreased or eliminated by increasing the rise time of the amplifier (to make pulse height less dependent on pulse rise time), by collimating the particles roughly parallel to the electrodes (to decrease rise time in a gridded chamber), and by using an ionization chamber which is capable of withstanding the voltages that would give maximum values of $X_{gs}/P$ between the electrodes (to increase the drift velocity and thus the rise time). (2) The saturation characteristics for alpha particles and fission fragments could be improved by having available higher $X_{gs}/P$ values between the electrodes, by using particles collimated roughly parallel to the source electrode (to decrease recombination effects), and by using a parallel-plate ionization chamber with guard rings to give a uniform field throughout the volume. (3) Multiplication and ratio of fields effects could be eliminated by using a two electrode chamber and particles collimated very closely parallel to the electrodes. However, such severe collimation would be difficult in practice. (4) Although the gases in the present experiment appeared to
have the characteristics of pure gases, it would be well to have a system for monitoring the purity. Since the drift velocity in many gases is very sensitive to impurities, the purity could be checked by incorporating a small auxiliary parallel-plate ionization chamber in the same gas system as the main chamber. By using a source of alpha particles which were collimated parallel to the electrodes, the drift velocity could be checked quickly and accurately. (5) The resolution of the fission distribution peaks was not as good as those given in the literature. It is now evident that more severe collimation would have increased the resolution of the fission distribution peaks. Although the number of fission fragments per unit of neutron flux would have been decreased, the decrease would have been largely in those fragments which traversed the greatest thickness in the source. (6) If the neutron flux were large enough, the resolution of the fission distribution peaks would be increased by using a smaller source thickness.

On the basis of the present experience it would appear that the use of total ion collection would have several advantages over that of electron collection. The chief advantages appear to be that an ungridded ionization chamber could be used without much collimation of the particles from the source. Elimination of the grid would remove the
effects of multiplication about the grid wires and of ratio of fields. Since both the negative and positive charges would be collected, the induced charge would not be a function of the orientation of the particle path so that severe collimation would not be necessary. Disadvantages would appear to be centered about a slow detecting system, and the microphonics, in particular.
ERROR ANALYSIS

For the purposes of this analysis the errors which entered into the results for the differences in ionization defects between gases are separated into two groups, the random and the systematic errors. The random errors usually show up for a large number of measurements as a scattering of the results about a mean value. The results may not be scattered about the true value because of the systematic errors. It is possible to check the magnitude of the random errors against the scattering of the results, whereas the systematic errors must be recognized, unless some of the results can be checked against a standard value.

In the analysis of the various results, the root mean square error, or standard deviation, will be used. The standard deviation was calculated in terms of the sum of the squares of the residuals, which are the differences between the mean value of a group of readings and the individual readings. The standard deviation is defined as the square root of the ratio of the summation of the squared residuals to one less than the number of readings.

In the following an attempt will be made to (1) describe the sources of the random errors and make an experimental estimate of their magnitude, (2) make an estimate of the total random error for the most probable light and
heavy fission ionizations and for the most probable alpha ionizations, (3) estimate the total random error for the most probable fission energies, (4) compare the magnitudes of the estimated total random errors with the standard deviations which were calculated from the variation of the ionization values from the mean, and (5) describe the possible systematic errors.

First, the sources of random errors in the present experiment are listed as follows: (a) calibration voltage, (b) drift in amplifier gain, (c) drift of the accelerator voltage in the oscillograph, and film movement (in the camera) in a direction parallel to the pulse height, (d) drift in the base line position, (e) photoelectric analyzer and location of the ionization distribution peaks, and (f) calibration equation. These will now be discussed in the same order.

(a) As given in the section on the electronics, the relative calibration voltage was held to an accuracy of about plus or minus .02 percent for both fission and alpha calibrations.

(b) Previously in this discussion the long time drift in the gain of the amplifiers was given as about plus or minus .2 percent for an eight hour period. If short time fluctuations in the amplifier gain were present, they would contribute to the width at half-maximum of the
distribution curves but not to any appreciable shift in the position of the peaks. Further, if the long time drift of the amplifier gain were linear with time, and most of the observations indicated at least a monotonic function for an eight hour period, the shift in the position of the fission ionization distribution curve would be compensated by the method of obtaining the calibration equation. Calibration distributions were recorded directly before and after the fission distribution, and the final calibration curve was taken as the average of the two. Thus the shift in the fission distribution curve was in the same direction as the shift in the calibration. Since the alpha particle and the calibration distributions were recorded on film in about twenty minutes, the drift of the amplifier gain was much less than that for the fission fragment distribution. Errors due to drift in amplifier gain for the most probable light and heavy fission ionizations and the average alpha ionization were estimated at plus or minus .1, .15, and .05 percent, respectively.

(c) Drift of the accelerator voltage and film movement in the camera were checked through use of the second beam of the dual-beam oscillograph. The beam was focused at one edge of the oscillograph tube at all times, had no signal applied to its deflection plates, and was turned on by the
same intensifier pulse as the first beam. Thus the variations of the heights of the dots on the film were an indication of the changes in the accelerator voltage and the movement of the film. Observations of this line of dots using the photoelectric analyzer showed a slow regular movement of about .14 percent, and superimposed on this there was occasionally a small general drift of about .2 percent. The period of the regular movement was much shorter than the shortest length of film used in a distribution, which would be one of the calibration distributions. The same slow regular motion was observed when the same camera was used to photograph another oscillograph, so that it appeared that the film movement was responsible for the observed variation. The small general drift was probably due to film movement also, although the drift of the oscillograph accelerator voltage cannot be eliminated from consideration. Again the short time movements of the film contributed to the width at half-maximum of the distribution peaks but probably did not cause appreciable shift in the position of the distribution peak. The film drift errors for the average alpha particle ionization and the most probable light and heavy fission ionizations were estimated to be about plus or minus .15, .15, and .2 percent, respectively.
(d) Drift in the base line of the first beam of the oscillograph was due to variations of the oscillograph voltages and to the low-frequency microphonics which arrived at the deflection plates. Drift due to the variations of the oscillograph voltages was checked indirectly by comparing the fission calibrations which were obtained before and after a fission distribution. There were no low-frequency microphonics visible in the noise level accompanying the fission calibration pulses. When the gain of the amplifiers was constant as checked by the electronic analyzer and when the fission calibration distributions were observed to agree within the error introduced by the film movement, the error due to the drift of the base line was assumed to be small compared to that of the film movement or to be a periodic variation. The signal to noise level for alpha particles was observed to be about 35 or larger for most of the distributions, whereas that for fission fragments was a factor of at least ten larger. Noise in the alpha pulse spectrum consisted mainly of low-frequency microphonics and high frequency noise from the first tube of the preamplifier. Thus the noise level influenced the width at half-maximum of the distribution peaks, but the error in the position of the alpha peaks due to the noise level was very small compared to errors described
in (b) and (c). A signal to noise ratio of 35 corresponded to shifts in pulse heights of plus or minus about 3 percent, and this appeared to largely account for the observed 6 percent width at half-maximum for the alpha distribution peaks.

(a) The magnitude of the errors involved in the photoelectric analysis and the location of the most probable alpha and fission ionizations are difficult to estimate except by observing the consistency of the results. Movement of the film through the photoelectric analyzer film holder in a direction parallel to the pulse heights was not significant compared to the width of the distribution peaks. The number of counts obtained in a particular channel was reproducible within about 2 percent. For a large number of channels across a distribution peak, the error in the shape of the peak was very insensitive to the error in a particular channel. The errors in the locations of the most probable ionizations using Method 1 were estimated by noting the ranges of the values of the most probable ionizations as the slopes of the lines passing through the inflection points on the sides of the distribution peaks were taken through relative extremes. The errors in the most probable ionization values for the alpha and the light and heavy fission peaks using Method 1 were estimated at
plus or minus .3, .5, and 1 percent, respectively. The errors in the location of the most probable ionizations using Method 2 resulted from the uncertainty of the values of the extrapolated ionization ($\approx .25$ percent) and from the placing of channels in or out of the distribution peaks on the bases of the criteria of Method 2 ($\approx .1$ percent). Errors for the most probable light and heavy fission ionizations using Method 2 were estimated at plus or minus .3 and .5 percent, respectively.

(f) Since the amplifier system appeared to be very linear over the range of pulse heights which were used, the error in the calibration equation due to the least square fitting procedure was neglected compared to some of the previously described errors.

Second, the total random errors for the most probable ionizations were obtained from the root of the sum of the squares of the errors listed above, mainly those from (b), (c), and (e). The total random errors which were assigned to the most probable values of the ionizations of the light and heavy fission fragments and the alpha particles were .55, 1.05, and .35 percent, respectively, for Method 1 and were .35, .55, and .35, respectively, for Method 2. The table at the top of Fig. 45 summarizes these estimated errors.
The largest estimated random error was that of the photoelectric analyzer and the location of the most probable ionizations, and it was described in section (e). The scattering of the results between the original and repeated data (Fig. 18), which were obtained from two independent photoelectric analyses of the same set of four complete runs, was an indication of the magnitude of this error for the case of analysis by a particular individual. The standard deviations which were indicated by the original and repeated data were obtained in the following way from Fig. 18. The mean was calculated for each pair of readings, and the two residuals for each pair were obtained. The residuals for the alpha ionizations of Method 1 were then used to find the standard deviation. The residuals of the light (\( \alpha \)) and the heavy (\( \beta \)) fission ionizations of Method 1 were used to find the respective standard deviations. Similarly the residuals of the light (\( \alpha \)) and the heavy (\( \beta \)) ionizations of Method 2 were used to find the standard deviations. When the standard deviations were translated to percentage using the lowest values of the ionizations for the base, the percentage errors were as follows. For Method 1, the errors for the most probable ionizations of the light and the heavy fragments and the average alpha particle were calculated to be .15, .25, and
.2 percent, respectively. For Method 2, the errors for the most probable ionizations of the light and the heavy fragments were both found to be .1 percent. The differences between these calculated errors and those given in section (e) would be due in part to the differences in viewpoints between various individuals who would locate the lines about the distribution peaks.

Using the alpha data which is given in Fig. 43a, a standard deviation was calculated and compared with the total random error which was estimated for the alpha particles. It was calculated from the most probable ionization values in the same gas but in different runs, i.e. Runs 1-2, 3-4, 7-8, 9-10, and 11-12. A mean value for each alpha particle in each gas was obtained, and the residuals for each value of alpha ionization were used to find the standard deviation. When the magnitude of the standard deviation was translated to percentage using an average alpha ionization as the base, the error was .45 percent for the alpha particles. This is to be compared with the value of .35 which was estimated.

Third, from the estimated total random errors for the alpha and fission most probable ionizations, the errors in the most probable fission energies were obtained, since the energies were given by the product of the ratio of the
ionizations and the alpha particle energies. The error in the alpha particle energies was very small compared to that in the ratio of the ionizations. Error in the most probable fission energy was obtained by taking the root of the sum of the squares of the alpha and fission errors. The percentage errors for the most probable light and heavy fission energies of Method 1 were estimated to be 0.65 and 1.1 percent, respectively. Those for Method 2 were estimated to be 0.5 and 0.65 percent, respectively.

Fourth, standard deviations were calculated for the most probable light and heavy fission energies from the values given in Fig. 43b. The mean values of the energies obtained in each gas were calculated for each of the most probable fission fragments. Residuals in each gas were then calculated, and the standard deviation was obtained using all the residuals for that fragment. In this manner the standard deviations of the most probable light and heavy fission energies were calculated to be 0.45 and 0.8 Mev, respectively. These standard deviations corresponded to errors of 0.5 and 1.3 percent, respectively. These values can be compared with the estimated values of 0.65 and 1.1, respectively. Using data from Fig. 43c, the standard deviations were also calculated for the fission energies of Method 2. The errors in the most probable light and heavy
fission energies were calculated to be .45 and .5 percent, respectively. These values can be compared with the estimated values of .5 and .65 percent, respectively. Estimated and calculated errors for the fission energies are tabulated in the center section of Fig. 45.

The values of the most probable light and most probable heavy fission energies in each gas were averaged as is indicated in Figs. 43c and 43f for Methods 1 and 2, respectively. The averaging process decreased the magnitude of the error in the average from that for the individual values. Assuming components having equal standard deviations, the standard deviation of the average is equal to the standard deviation of one of the components divided by the root of the number of components. Two values of the most probable light and heavy fission energies were averaged for each gas except argon, which had four values, and argon plus 5 percent nitrogen, which had only one. Thus, the estimated errors for the averages in argon and in the other gases were decreased by a factor of 2 and 1.4, respectively, over that for a single value. A tabulation of the estimated errors for the average fission energies in the various gases is given in the extreme lower left corner of Fig. 45.

Since the difference in ionization defects between two
gases was obtained by subtracting the fission fragment energies in the gases, the total estimated error in the difference, neglecting systematic errors, was obtained by taking the root of the sum of the squares of the errors for each fission energy. The tabulation in the extreme lower right corner of Fig. 45 shows the errors which have been estimated for the differences in ionization defects between argon gas and the other gases. Numbers in parentheses are in Mev.

The estimated errors in the values of the extrapolated ionizations were about the same as those for the most probable light fission fragment except for that in section (e). The root of the sum of the squares of the individual errors yielded an estimated error of about .3 percent for the extrapolated ionizations. The error in the extrapolated energies was a combination of the errors in the extrapolated ionization and the alpha ionization, and it was estimated to be .45 percent. The standard deviation of the extrapolated energy values given in Fig. 43c was calculated. Mean values for each of the gases were found, and the residuals for each run were obtained. Using all of the residuals, the standard deviation for the extrapolated energy was calculated to be .5 percent. Fig. 45 also includes the summary for the error analysis of the extra-
polated energies.

Fifth, the systematic errors which must be considered along with the results are listed as follows: (g) variation of the fission and alpha saturation curves between gases, (h) differences in the rise times of the ionization pulses for alpha particles and fission fragments, (i) gas purity and changes in the constituents of the gases between runs in the same gas, (j) thickness of the source and the collimation factor, and (k) differences between fission and alpha ionization losses in the collimator.

(g) In the present experiment the pulse height sensitivity of the equipment was good enough that small slopes of the saturation curves were observable. Complete saturation for alpha particles and fission fragments appeared to have been achieved for nitrogen gas, argon plus 5 percent nitrogen, and argon plus 3 percent carbon dioxide gas mixtures. For the cases of argon, helium, and neon gases, the saturation curves for both alpha particles and fission fragments exhibited a small positive slope. Since the saturation curves for the alpha particles and the fission fragments appeared to have about the same characteristics, it was probable that the same degree of saturation had been achieved. It was assumed that the small slope was not due to an effect which would differentiate between the alpha and
fission ionizations. In this case the ratio of the fission to alpha ionizations would not be appreciably affected.

(h) In a previous section, Determination of Saturation Curves, the effect of differences in rise times between the alpha particles and fission fragments stopped in argon gas at about 400 mm Hg was discussed. It was pointed out in this case that the difference between the rise times increased the ratio of the most probable fission to alpha ionizations (and thus the fission energy) by about 1/2 percent. Since the decrease in pulse height due to the amplifier characteristics is directly proportional to the square of the ratio of the pulse rise time to the amplifier rise time, 6 the differential rise time effect between alpha particles and fission fragments becomes rapidly smaller for decreasing pulse rise times. For example, the alpha pulse rise time in neon gas was about one-half that for the argon above, and the differential rise time effect between the alpha and fission rise times was calculated as about .15 percent. Run 5 was made with argon gas at 1 atmosphere, and the alpha pulse rise times were nearly a factor of two faster. However, the fission energies which were obtained were slightly lower than the average argon fission energies which included three runs at 1/2 atmosphere. For the present resolution of the fission energies, it was not
deemed necessary to make a correction for the differential rise time effect.

(i) Comparison of the values of $W\alpha$ which were calculated from the data (Fig. 44) with those of Jesse et al.,$^{27}$ who used very pure gases, have good agreement. Since the $W\alpha$ values of neon and helium gases vary a great deal between pure and contaminated gases, it was believed that the present purification process was effective in removing most of the contamination gases. No variation in the purity of the gases was detected between runs.

(j) The fission energies were not corrected for the losses of alpha and fission energies in the source thickness. Since the same source and collimator were used throughout the experiment, the energy loss to the source was not a function of the type of gas in the chamber.

(k) Since the collimator holes were relatively large in diameter compared to their thickness, the electric fields in the collimator holes were expected to be large enough to remove most of the free electrons. If appreciable error were introduced into the ratio of fission to alpha ionizations by the loss of electrons in the collimator, it would be relatively constant between those gases in which the particle path lengths were about the same.
### Table: Random Error Sources

<table>
<thead>
<tr>
<th>RANDOM ERROR SOURCES</th>
<th>ESTIMATED ERRORS IN THE MOST PROBABLE IONIZATIONS (PERCENT)</th>
<th>ERRORS IN THE EXTRAPOLATED FRAGMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>METHOD 1</td>
<td>METHOD 2</td>
</tr>
<tr>
<td></td>
<td>ALPHA LIGHT HEAVY</td>
<td>LIGHT HEAVY</td>
</tr>
<tr>
<td>(a)</td>
<td>.02 .02 .03</td>
<td>.02 .03</td>
</tr>
<tr>
<td>(b)</td>
<td>.05 .15 .15</td>
<td>.15 .15</td>
</tr>
<tr>
<td>(c)</td>
<td>.15 .15 .20</td>
<td>.15 .20</td>
</tr>
<tr>
<td>(d)</td>
<td>.05 .05 .07</td>
<td>.05 .07</td>
</tr>
<tr>
<td>(e)</td>
<td>.3 .5 1.</td>
<td>.3 .5</td>
</tr>
<tr>
<td>(f)</td>
<td>.03 .03 .04</td>
<td>.03 .04</td>
</tr>
<tr>
<td>TOTAL</td>
<td>.35 .55 1.05</td>
<td>.35 .55</td>
</tr>
<tr>
<td>CALC. (e)</td>
<td>.2 .15 .25</td>
<td>1. 1</td>
</tr>
</tbody>
</table>

**CALCULATED** .45 USING ALPHA DATA FROM FIG. 43a

### Table: Error in Fission Energies (Percent)

<table>
<thead>
<tr>
<th>ESTIMATED ERROR IN FISSION ENERGIES (PERCENT)</th>
<th>ERROR IN EXTRA ENERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>METHOD 1</td>
<td>METHOD 2</td>
</tr>
<tr>
<td>LIGHT HEAVY</td>
<td>LIGHT HEAVY</td>
</tr>
<tr>
<td>ESTIMATED</td>
<td>.65 .1.5</td>
</tr>
<tr>
<td>CALCULATED</td>
<td>.5 .1.3</td>
</tr>
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</table>

### Table: Estimated Error for the Average Fission Energies

<table>
<thead>
<tr>
<th>GAS</th>
<th>METHOD 1</th>
<th>METHOD 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LIGHT HEAVY</td>
<td>LIGHT HEAVY</td>
</tr>
<tr>
<td>A+9% N₂</td>
<td>.65 .1.</td>
<td>.5 .65</td>
</tr>
<tr>
<td>A</td>
<td>.35 .55</td>
<td>.25 .35</td>
</tr>
<tr>
<td>OTHERS</td>
<td>.45 .8</td>
<td>.35 .45</td>
</tr>
</tbody>
</table>

**ESTIMATED PERCENT ERROR FOR AΔf — XΔf**

<table>
<thead>
<tr>
<th>GAS</th>
<th>METHOD 1</th>
<th>METHOD 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LIGHT HEAVY</td>
<td>LIGHT HEAVY</td>
</tr>
<tr>
<td>A+9% N₂</td>
<td>.75 .25</td>
<td>.55 .75</td>
</tr>
<tr>
<td>A</td>
<td>(.7) (.8)</td>
<td>(.5) (.5)</td>
</tr>
<tr>
<td>OTHERS</td>
<td>.6 .1</td>
<td>.45 .6</td>
</tr>
</tbody>
</table>

### Fig. 45 Summary of the Error Analysis
The ionization defects of the most probable fission fragments stopped in helium, neon, nitrogen, argon plus 5 percent nitrogen, and argon plus 3 percent carbon dioxide were measured relative to those of argon. These measurements of the differences between ionization defects for fission fragments between gases were made under the assumption that the alpha particle ionization defects in the gases were very small compared to the alpha particle initial energy. The conditions on the working equation would also be satisfied if $x^R \Delta \alpha^x$ were equal to $a^R \Delta \alpha^a$.

Differences in the ionization defects between argon and helium gases were observed to be about one-third as large as those which were expected on the basis of increased ionizing efficiency for lighter recoil gas atoms. The smaller observed differences might be due to changes in the average charge of fission fragments between gases, double ionization in helium gas, and metastable states in helium gas. Differences in the defects between argon and neon gases were not regarded as significant. Since the masses differ by only a factor of two, a large difference was not expected. Large differences in the defects between argon and nitrogen gases and between argon and argon plus carbon dioxide were observed.
These were not expected on the basis of the variation of the ionizing efficiency with the mass of the recoil gas atoms, or atomic ionization defect. They were explained qualitatively in terms of a molecular ionization defect. The large magnitude of the difference between argon and argon plus 3 percent carbon dioxide was surprising in view of the small quantity of carbon dioxide present. Differences in the defects between argon and argon plus 5 percent nitrogen were not regarded as significant although the presence of 5 percent of a molecular gas might be expected to give rise to a small difference.

The differences between ionization defects in argon and argon plus carbon dioxide gases was used as a basis to suggest that the ionization defect attributed to argon gas might not be as large as has been indicated and that the discrepancy in the measurements of the ionization defect for alpha particles in argon gas might be resolved.

The operating characteristics of a gridded parallel-plate ionization chamber were investigated, and the particular effects, such as electron multiplication about the grid wires, ratio of fields for complete electron collection, rise time of ionization pulses, and alpha and fission saturation curves, were observed as a function of the chamber gases. A correlation was observed between the minimum ratio of
fields necessary for complete electron collection in a gas and the calculated magnitude of the electron diffusion in the gas. Mention of this correlation has not been found in the literature. Multiplication of electrons about the grid wires was observed for argon and neon gases, and mention of this effect in gridded parallel-plate ionization chambers has not been found in the literature.

Alpha particle saturation curves in the various gases have been observed with much greater precision than those which have been found in the literature.

The experience with electron collection in the gridded parallel-plate ionization chamber of the present experiment indicated that when design conditions made it possible, it would be well to incorporate the following features: parallel electrodes with guard rings, a source of particles collimated parallel to the electrodes, a two-electrode chamber instead of a gridded chamber, a chamber which can withstand maximum values of $X/P$ between the electrodes, and the addition of a system to monitor the purity of the gas.

A relatively simple method of making large, uniform, natural uranium sources was devised and used in the present experiment. It appears readily applicable to making source thicknesses over the range from a few micrograms to several
milligrams per square centimeter.

A linear, high gain (≈ 5000) shaping amplifier having a rise time and a clipping time of about 30 microseconds was designed and constructed.

The use of mixtures of argon plus carbon dioxide gases in the present chamber has been found to produce some undesirable characteristics. Saturation characteristics for alpha particles appeared to be a function of the percent of carbon dioxide present in the argon and of the pressure of the gas mixture. Mixtures of argon and nitrogen gases appeared to give the same desirable characteristics as the argon and carbon dioxide mixtures without the apparently undesirable effects.

The relative values of \( W_\alpha \), using electron collection in the present experiment, compared well with the literature values, which were obtained using total ion collection.

On the basis of the results of the present experiment it appeared that a number of further investigations would be of particular interest for the operation of parallel-plate ionization chambers and for the study of the fundamental energy loss processes. They are listed as follows: (1) More detailed investigation of the fundamental processes in an ionization chamber using argon plus carbon dioxide and further investigation of the features of argon plus
nitrogen mixtures. (2) Investigation of the difference in fission fragment ionization defects between helium gas and helium plus several tenths percent of argon and between helium gas and helium plus 3 percent carbon dioxide. (3) Investigation of the difference in fission fragment ionization defects between argon plus 3 percent of carbon dioxide and argon plus higher or lower percentages of carbon dioxide. (4) Investigation of alpha particle and fission fragment saturation curves in various gases using both electron collection and total ion collection in the same chamber. (5) Investigation of the alpha particle and fission fragment ionization defects between gases using both electron collection and total ion collection in the same chamber.
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