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Ionization defect for alpha particles in various gases

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The ionization produced by the Li$^{7*}$ and beta-particles from the reaction B$^{10}$(n, beta)Li$^{7*}$ as they were stopped in argon, argon-nitrogen, and argon-carbon dioxide gas mixtures was measured. A gridded parallel-plate ionization chamber employing electron collection was used. Plutonium alpha particles were used for calibration and the ionization electron pulses were amplified and sorted with an electronic pulse height analyzer. The neutron source was a 300 kev linear positive ion accelerator utilizing the D-D reaction. The neutrons were thermalized by blocks of paraffin stacked around the chamber. The thin boron film was made by evaporating boron enriched to 95 percent with B$^{10}$ onto an aluminum backing. The gas mixtures were purified by continuous circulation over hot calcium-magnesium alloy.

Keywords
Ames Laboratory

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UNITED STATES ATOMIC ENERGY COMMISSION

IONIZATION DEFECT FOR ALPHA PARTICLES IN VARIOUS GASES

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August 1955

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IONIZATION DEFECT FOR ALPHA PARTICLES
IN VARIOUS GASES*

by

David W. Curtis and Glenn Miller

ABSTRACT

The ionization produced by the Li\(^{7}\)* and \(\alpha\)-particles from the reaction \(^{10}\text{B}(n,\alpha)Li^{7}\)* as they were stopped in argon, argon-nitrogen, and argon-carbon dioxide gas mixtures was measured. A gridded parallel-plate ionization chamber employing electron collection was used. Plutonium alpha particles were used for calibration and the ionization electron pulses were amplified and sorted with an electronic pulse height analyzer. The neutron source was a 300 kev linear positive ion accelerator utilizing the D-D reaction. The neutrons were thermalized by blocks of paraffin stacked around the chamber. The thin boron film was made by evaporating boron enriched to 95 percent with \(^{10}\text{B}\) onto an aluminum backing. The gas mixtures were purified by continuous circulation over hot calcium-magnesium alloy.

The energies for the alpha particles and lithium recoils as calculated from the measured ionization yields were 1.468 ± 0.002 and 0.782 ± 0.004 Mev in argon, 1.460 ± 0.002 and 0.784 ± 0.002 Mev in argon plus 2 percent nitrogen, and 1.444 ± 0.002 and 0.774 ± 0.002 Mev in argon plus 5 percent carbon dioxide. The uncertainties quoted are the standard deviations for the series of measurements. These results should be compared to the energies 1.473 ± 0.002 Mev for the alpha particles and 0.841 ± 0.002 Mev for the lithium recoils determined from conservation of momentum. The 5 kev ionization defect measured for the alpha particles in argon was assumed to be due to source thickness. This leads to a 6 kev correction to be applied to all values obtained for the lithium recoils.

The results of this experiment along with those of other investigators demonstrate the constancy of the average energy required to produce an ion pair, \(W\), for alpha particles in argon above an energy of 1.4 Mev. Further,
ionization defects of $8 \pm 3$ and $24 \pm 3$ kev were obtained for the alpha particles from the reaction in argon plus nitrogen and in argon plus carbon dioxide respectively. These results show the existence of a molecular defect for low energy alpha particles in the presence of polyatomic gases as suggested by the measurements of Herwig and Miller on fission fragments.

The ionization defect of about 50 kev obtained for the lithium recoils in argon gas is subject to considerable uncertainty due to conflicting evidence on the existence of ion recombination. This evidence would seem to indicate that there may be a fundamental difference between electron collection and total ion collection not as yet understood. Ionization defects of $51 \pm 3$ and $61 \pm 3$ kev were obtained for the lithium recoils in argon plus nitrogen and in argon plus carbon dioxide respectively. The portion of each defect which may be attributed to the presence of a polyatomic gas can not be obtained from this experiment.
INTRODUCTION AND LITERATURE SURVEY

Theoretical Discussion

Energetic atomic particles passing through matter lose energy through ionization, excitation, and elastic collisions with atoms of the stopping material. Niels Bohr published a comprehensive theoretical discussion of these phenomena in which he surveyed the experimental contributions up to that time. The energy loss processes are generally thought of as being of two kinds, atomic or elastic encounters and electronic or inelastic encounters. In atomic encounters momentum and kinetic energy are transferred to translatory motion of the stopping atoms as a whole. In electronic encounters energy is transferred to the individual electrons of the stopping material leading to excitation and ionization.

A criterion developed by Bohr is useful in determining which type of encounter predominates along the path of a particle as it is being stopped in matter. The criterion is based on the velocity of an electron in the ground state of the Bohr model of the hydrogen atom \( V_0 = \frac{e^2}{\hbar} \). The cross-section for atomic encounters is small for incident particle velocities much greater than \( V_0 \) and increases as the velocity decreases reaching a maximum value of \( \pi a^2 \) for velocities much less than \( V_0 \) where \( a \) is the sum of the atomic radii. At incident particle velocities which are much greater than \( V_0 \), the cross-section for electronic encounters is much larger than that for the atomic encounters but is greatly reduced at velocities much less than \( V_0 \). Thus for velocities much less than \( V_0 \), atomic encounters predominate.

If the incident particle is a positive ion such as an alpha particle, the picture is further complicated by the capture and loss of electrons by the incident particle. For velocities much greater than \( V_0 \) the cross-section for loss predominates and the alpha particle is doubly charged. For velocities much less than \( V_0 \) the reverse is true and the alpha particle is singly charged or neutral.

A convenient method for determining the energy of atomic particles ejected by nuclei is to measure the number of ion pairs formed as the particles are stopped in a gas. For an incident particle stopped in a gas the average energy per ion pair, \( W \), is defined as \( E/I \) where \( E \) is the initial energy of the particle and \( I \) is the total number of ion pairs formed in the stopping process. For incident particle velocities much less than \( V_0 \), the ionization efficiency for the incident particle and for the recoil gas atoms produced is low. This leads to a high value for \( W \). As the velocity of the incident particle increases the ionization efficiencies for the primary particle and for the recoil gas atoms increase. This leads to a decrease in the value of \( W \). Further, as the velocity becomes much greater than \( V_0 \) electronic encounters predominate.
and \( W \) approaches a constant value \( W' \).

The term ionization defect was introduced as a convenient experimental parameter by Knipp et al.\(^2\) in a theoretical discussion which attempted to describe the energy-ionization relationship for heavy particles stopped in a gas and by Hanna\(^3\) in an experimental paper on the ionization produced by low energy alpha particles. The ionization defect \( (\Delta = E - IW') \) is a slowly varying function of the initial velocity of the incident particle. It has a finite value for zero ionization which increases to a maximum value, \( \Delta' \), for high incident velocities.

**Experimental Results of Other Investigators**

Cranshaw and Harvey\(^4\), using a gridded parallel-plate ionization chamber employing electron collection, measured the relative ionization produced by alpha particles from several natural alpha emitters which were stopped in commercial argon gas. Six groups of alpha particles ranging in energy from 5 to 9 Mev whose energies were known from magnetic deflection experiments were used. A least squares plot of relative ionization versus energy resulted in a straight line which had an intercept on the energy axis at \( 85 \pm 10 \) kev. This experiment was later repeated by Jesse et al.\(^5\) in a cylindrical ionization chamber employing total ion collection and using spectroscopically pure argon gas. The straight line obtained by these investigators appeared to pass through the origin within experimental error.

Hanna\(^3\) and Rhodes et al.\(^6\) measured the ionization produced by the \( \text{Li}^{7*} \) and \( \alpha \)-particles from the reaction \( \text{B}^{10}(n,\alpha)\text{Li}^{7*} \) which were stopped in purified argon gas to which had been added to a small amount of carbon dioxide. In each case electron collection was employed and alpha particles from natural alpha emitters were used for calibration. The kinetic energy of the alpha particles from the reaction as calculated by Rhodes et al. from independent data is \( 1.473 \pm 0.002 \) Mev. Hanna obtained an ionization defect of \( 42 \pm 13 \) kev and Rhodes et al. obtained an ionization defect of \( 29 \pm 10 \) kev for these alpha particles. Facchini et al.\(^7\) measured the ionization produced by the \( \text{H}^{3} \) and \( \alpha \)-particles from the reaction \( \text{Li}^{6}(n,\alpha)\text{H}^{3} \) which were stopped in argon gas. A parallel-plate gridded ionization chamber employing electron collection was used; the argon was purified by passing over hot calcium; and the chamber was calibrated with alpha particles from natural uranium. The kinetic energy of these alpha particles from this reaction as calculated from magnetic deflection measurements made by Tollestrup et al.\(^8\) is \( 2.056 \pm 0.010 \) Mev. The ionization defect found for these alpha particles was \( -3 \pm 14 \) kev.

Herwig and Miller\(^9\) measured the ionization produced by fission fragments from the fast neutron fission of natural uranium which were stopped in gas mixtures of argon, argon plus 5 percent nitrogen, and
argon plus 3 percent carbon dioxide. The argon was purified by circulating over hot calcium-magnesium alloy. A gridded parallel-plate ionization chamber employing electron collection was used. Calibration was accomplished by means of alpha particles from natural uranium. The energies for the most probable light and heavy fragments as calculated from ionization measurements were 1 Mev less in argon plus nitrogen than in argon and 3 Mev less in argon plus carbon dioxide than in argon plus nitrogen. These differences were explained by assuming that some of the energy which would normally produce ionization was lost to molecular excitation and dissociation. It was further assumed that the fraction of the energy lost in this manner was a function of the complexity of the molecules and of the density of ionization along the track. Herwig and Miller suggested that this "molecular defect" might explain the magnitude of the ionization defect for low energy alpha particles found by previous investigators. Two experimental papers by Jesse and Sadauskis and one by De Juren and Rosenwasser will be discussed in a later section.

It has been the purpose of this investigation to determine whether or not a "molecular defect" exists for 1.5 Mev alpha particles. To accomplish this objective the ionization defect for alpha particles from the reaction $^{7}\text{Li} \rightarrow \text{Li}^{7+}$ was measured in argon, argon plus 2 percent nitrogen, and argon plus 5 percent carbon dioxide.

**METHOD OF PROCEDURE**

The total ionization produced by a particle which was stopped in the chamber gas was measured in a gridded parallel-plate ionization chamber which employed electron collection. The motion of the electrons in the electric field between the grid and collector electrodes induced a voltage pulse on the collector electrode whose magnitude was directly proportional to the number of ion pairs created by the particle. The voltage pulse produced at the collector electrode was amplified by a linear amplifier and classified according to pulse height.

Measurements were made in each gas mixture on the excited lithium recoils and on alpha particles from the reaction $^{7}\text{Li} \rightarrow \text{Li}^{7+}$ as well as on alpha particles from the radioactive decay of $^{239}\text{Pu}$. The pulse height analyzing system used was capable of sorting voltage pulses ranging in size from 150 to 400 volts. The amplifier gain which would confine the $^{239}\text{Pu}$ alpha particle pulse height distribution to this region would give little detail to the shape of the distribution curve. Thus, when measurements were made on these particles, it was necessary to insert an expander amplifier before the pulse height analyzing system. A pulse height calibrator was used for accurate comparison of the different particle pulse heights.
Lithium recoils and alpha particles from the reaction $\text{B}^{10}(n, \alpha)\text{Li}^7$ were obtained from a source enriched to 95 percent with $\text{B}^{10}$ which was irradiated with thermalized neutrons. The neutrons were obtained from a linear accelerator using the reaction $\text{D}(\text{D},n)\text{He}^3$ at 200 kev and were thermalized by three inches of paraffin placed between the accelerator target and the chamber. Paraffin blocks were also stacked around the chamber to serve as neutron reflectors. $\text{Pu}^{239}$ alpha particles were obtained from a separate source located in the center of the boron film. An ionization distribution curve was obtained for each type of particle by measuring the total ionization produced by individual particles and by making a graph of the number of particles versus ionization. The data for the lithium recoils and alpha particles from the reaction were taken in the presence of $\text{Pu}^{239}$ alpha particles. This was made possible by the non-blocking property of the main amplifier which will be described later.

The position of the peak of each ionization distribution curve was determined by the method of diameters developed by Cranshaw and Harvey\(^4\) and was taken as a measure of the ionization produced by the corresponding type of particle. For the purpose of this discussion let $I_p$ denote the average ionization produced by the $\text{Pu}^{239}$ alpha particles, $I_{\text{Li}}$ that produced by the lithium recoils, and $I_\alpha$ that produced by the alpha particles from the reaction. Then

\begin{align}
(1) \quad E_\alpha^i &= I_\alpha W_p^i = E_p (I_\alpha / I_p) \\
(2) \quad E_{\text{Li}}^i &= I_{\text{Li}} W_p^i = E_p (I_{\text{Li}} / I_p) \\
(3) \quad \Delta \alpha &= E_\alpha - E_\alpha^i = E_\alpha - E_p (I_\alpha / I_p) \\
(4) \quad \Delta \text{Li} &= E_{\text{Li}} - E_{\text{Li}}^i = E_{\text{Li}} - E_p (I_{\text{Li}} / I_p)
\end{align}

where $E_x$, $E_x^i$, $W_x^i$, and $\Delta_x$ are the true energy, apparent energy, energy per ion pair, and ionization defect respectively for particle $x$. For alpha particles from natural alpha emitters, $W$ is practically equal to $W_p^i$. Thus, $W_p$ was actually used in the calculations ($W_p^i \approx W_p = E_p / I_p$).
EXPERIMENTAL EQUIPMENT

Ionization Chamber

The theory of pulse formation in a gridded parallel-plate ionization chamber has been extensively treated by many authors, such as Wilkinson\textsuperscript{13} and Bunemann \textit{et al}.\textsuperscript{14}, and will not be given here.

Fig. 1 shows a schematic diagram of the ionization chamber. The chamber housing was cylindrical in shape with inside dimensions of 6 inches in diameter and 6 inches in depth. It was made from a section of brass tubing having a wall thickness of 0.375 inch and was fitted with endplates machined from 0.5 inch thick brass stock. The lower endplate was silver-soldered to the brass tubing and 7 brass bolts 0.375 inch in diameter, not shown in the figure, were used to apply pressure to Teflon gasket (G) between the upper endplate and the chamber wall to effect a vacuum seal. The collector electrode (B) and the source electrode (C) were supported from the upper and lower endplates respectively by porcelain insulators. Negative voltage for the source and positive voltage for the collector were applied by means of glass-to-metal terminals (F) and the electrical connections were maintained by spring contacts. A shield box (H) containing a filter composed of a resistor and a capacitor was placed over the glass-to-metal seal for the source plate. The preamplifier (I) served as the shield for the external connection to the collector. The grid (A) was mounted on a brass cylinder which was fastened to the upper endplate with metal screws. The boron source was deposited on an aluminum backing (D) which was fastened to the source plate with metal screws. The Pu\textsuperscript{239} source had a platinum backing which was soft-soldered to a button (E) in the middle of the source plate. Gas was admitted through a needle valve (L) and the chamber was equipped with the dual pressure gauge (K). Copper tubing (J) having an inside diameter of 0.375 inch joined the chamber to a gas purifier which will be described later.

The source and collector plates were 5 and 4.25 inches in diameter respectively and were machined from aluminum stock 0.25 inch thick. The source plate was fitted with an aluminum skirt 0.024 inch thick which extended 0.75 inch toward the collector. This served to bend the lines of force toward the collector reducing the loss of electrons due to diffusion to the chamber wall. The grid consisted of steel wires 0.0036 inch in diameter which were parallel to each other and spaced 0.080 inch apart. The wires were soft-soldered to the supporting brass cylinder. The source-grid and grid-collector spacings were 1.4375 inches and 0.1875 inch respectively.

Bunemann \textit{et al}.\textsuperscript{14} calculated an equation which indicated the inefficiency, $\sigma$, with which the grid shields the collector from a charge in the grid-source region. The equation is

$$\sigma \approx \frac{\xi}{2 \pi d_{gc}} \ln \frac{\xi}{2 \pi r},$$

where $\xi$ is the distance from the grid to the source plate, $d_{gc}$ is the distance between the grid and collector, and $r$ is the radius of the chamber.

\textsuperscript{13} W. M. Wilkinson.

\textsuperscript{14} K. Bunemann, \textit{et al}.
FIG. 1 SCHEMATIC DIAGRAM OF THE IONIZATION CHAMBER
where \( \xi \) is the spacing between the grid wires, \( r \) is the radius of the grid wires, and \( d_s \) is the grid-collector spacing. Consider a charge \( Q \) in the grid-source region a distance \( b \) from the grid. Let \( d_g \) be the grid-source spacing. Then, the charge \( q \) induced on the collector due to \( Q \) is given by the equation

\[
q = Q \sigma \left( \frac{1}{b} - \frac{1}{d_g} \right).
\]

The value of \( \sigma \) for this chamber was calculated to be 13.5 percent.

Electronic Equipment

Fig. 2 shows a block diagram of the experimental equipment which was used to produce, amplify, shape, and sort the voltage pulses. Negative and positive voltages for the source and collector electrodes respectively were supplied by batteries. The voltage for the collector electrode was passed through the input circuit of the preamplifier. The voltage pulses formed at the collector electrode of the chamber were amplified by means of a preamplifier and a main amplifier. The gain of the preamplifier and main amplifier system was adjustable so that output voltage pulses from the main amplifier were of the order of 30 volts.

When ionization data were taken on the alpha particles from the decay of Pu239, pulses from the main amplifier were fed into an expander amplifier. The expander amplifier was a device which amplified that portion of each pulse in excess of a fixed voltage. The remainder of the pulse was not transmitted. The expander amplifier was by-passed while all other data were being obtained.

The pulse lengthener circuit was used to shape the pulses suitably for accurate pulse height analysis. The intensifier circuit was used in conjunction with the pulse height analysis system. The pulse height analysis system consisted of a Los Alamos model 1000 amplifier and an electronic 10 channel pulse height analyzer and was the same system used by Herwig and Miller. The single channel pulse height analyzer was used to monitor the reaction rate of the \( {\text{B}}^{10}(n,\alpha){\text{Li}}^7 \) reaction. The electronic equipment was calibrated with a precision pulse generator constructed for the Ames Laboratory by C. E. Harper. Pulses from the pulse generator were applied to the source electrode of the ionization chamber and appeared at the collector electrode due to the inter-electrode capacitance of the chamber. The size of voltage pulses at the output of the pulse generator was controlled by a helipot with 0.1 percent linearity.

Fig. 3 shows a circuit diagram of the preamplifier. It consisted of three tubes in a feedback loop of three isolated by a cathode
FIG. 2 BLOCK DIAGRAM OF THE EXPERIMENTAL EQUIPMENT
FIG. 3  PREAMPLIFIER
follower which was used to feed the signals through a 35 foot coaxial cable to the main amplifier. The cathode resistor of the cathode follower was located at the input to the main amplifier and served as the coarse gain control. A 120 cycle parallel-T rejection filter was placed before the output cathode follower to suppress microphonics and pick up signals in that frequency range originating at the grid wires in the ionization chamber. Direct current for the tube filaments was supplied by a 6 volt storage battery in parallel with a 4 ampere tapering charger.

When there was no voltage between the electrodes of the ionization chamber, the noise at the output of the electronic equipment was almost exclusively that arising from the first tube of the preamplifier. The noise level was minimized by shock mounting the first tube to the tube rack and the tube rack to the preamplifier case and by exercising care in the selection of the first tube.

The main amplifier, Fig. 4, consisted of two feedback loops of four tubes with a cathode follower output. Tubes T-1, 2, 3, 4 formed the first loop and tubes T-5, 6, 7, 8 the second loop. The amplifier was designed for negative input pulses and employed direct coupling within each loop. The two loops were identical in construction and each had a gain of approximately 95. Tubes T-3 and T-7 provided voltage platforms for the operation of tubes T-2 and T-6 respectively. Parallel-T rejection filters of 48 and 60 cycles were placed at the input and output respectively to suppress grid wire microphonics and pickup from the tube filaments. The integrating and clipping times of the amplifier were controlled by resistor-capacitor networks located between the loops. The gain of the preamplifier and main amplifier system was made insensitive to variations in the rise time of voltage pulses from the chamber by making the rise and clipping RC time constants of the main amplifier equal and longer than the longest rise time of the pulses as recommended by Wilkinson.

The direct coupling feature was responsible for the non-blocking property of the main amplifier. Negative voltage pulses at the input would appear as positive pulses at the plates of T-1 and T-5. If the pulse height exceeded the grid bias of either T-2 or T-6 the top of the pulse would be clipped off as a result of grid current and the grid bias would return to its original value as soon as the pulse had passed. Due to the direct coupling feature a change in the steady state value of the voltage at any point within a loop would result in changes in potential at all points throughout the loop. Thus, the cathode potential of tubes T-4 and T-8 was externally monitored during operation and could be reset by adjusting the grid biases of tubes T-3 and T-7 respectively.

The expander amplifier, Fig. 5, consisted of a phase inverter, tube T-1, and a diode, tube T-2, in parallel followed by the first loop of a
FIG. 4. MAIN AMPLIFIER
FIG. 5. EXPANDER AMPLIFIER
Bell-Jordan amplifier, tubes T-3,4,5, isolated by a cathode follower, tube T-6. The cathode of the diode was maintained at a positive potential of 27 volts. At the output of the diode the signal was combined with a signal of the opposite polarity from the phase inverter to compensate for the capacitance of the diode.

Fig. 6 shows a diagram of the pulse lengthener circuit. A negative pulse from the main amplifier or the expander amplifier was applied to a phase inverter, tube T-1. The pulse arising at the cathode of the phase inverter was amplified 1.5 times and inverted by tube T-2. Low impedance outputs for this pulse and for the accompanying pulse from the plate of the phase inverter were obtained from cathode followers T-5 and T-3 respectively. The amplified pulse caused the cathode of T-5 to rise and cut off one of the twin diodes, T-4. This allowed T-3 to charge a condenser to the peak value of the input voltage pulse through the other diode. The voltage across the condenser remained at the peak value until the potential of the cathode of T-5 dropped to less than this value at which time the condenser was discharged through the cathode resistor of T-5.

The noise level at the output of the 10 channel analyzer was a function of the band width used in the main amplifier. When there was no voltage between the electrodes of the ionization chamber, the root mean square noise was equivalent to 27 kev when integrating and clipping RC time constants of 5 microseconds were used in the main amplifier. When these time constants were increased to 10 microseconds, the root mean square noise was equivalent to 36 kev. With voltage on the collector electrode of the ionization chamber the root mean square noise was increased to 31 and 41 kev respectively for the above time constants. This increase was explained as due to microphonics from the grid wires in the chamber and leakage of the coupling condenser between the collector electrode and the preamplifier.

TECHNIQUES

In the course of this experiment a number of special techniques were used. They will be described in the following under the topics of main amplifier, source preparation, gas purification, and background reduction.

Main Amplifier

Ionization chamber pulses due to alpha particles from the decay of Pu$^{239}$ were about 6 times larger than the pulses due to the lithium recoil particles. The non-overloading property of the main amplifier allowed the Pu$^{239}$ source to be permanently fixed in the chamber. Thus,
FIG. 6. PULSE LENGTHENER CIRCUIT
data could be taken alternately on the Pu$^{239}$ alpha particles used for calibration and on the particles from the reaction. The maximum rise times of pulses from the chamber occurred for Pu$^{239}$ alpha particles in purified argon. The rise times of these pulses varied from less than 1 to about 4 microseconds. The use of integrating and clipping RC time constants longer than twice the longest rise time of pulses from the chamber made the magnitude of the amplified pulses relatively independent of the changes in rise time of incoming pulses. Furthermore, the reduction in the band width achieved was instrumental in reducing the noise level.

Source Preparation

The boron source used was prepared by vacuum sublimation of powdered metallic boron enriched to 95 percent with B$^{10}$. The sublimation took place from an alundum crucible made by painting tungsten wire 0.02 inch in diameter in the form of a closely wound conical coil with a water suspension of Al$_2$O$_3$ and allowing it to dry in air. The crucible was then heated slowly to a temperature of 1800°C in a vacuum by a current in the tungsten wire until a vacuum of $10^{-6}$ mm Hg was achieved. The backing for the source was an aluminum disk made from aluminum stock 0.024 inch thick. The source backing was highly polished to remove local nonuniformities in the surface which might lead to an increase in the apparent source thickness. The source backing was then mounted in the vacuum system 7.5 inches above the apex and perpendicular to the axis of the crucible. Enough powdered boron was added to the crucible to give an area density to the source of 8 micrograms per square centimeter if uniform coverage of the source backing were achieved. The crucible was then heated to a temperature of 1400°C in a chamber evacuated to a pressure of less than $10^{-5}$ mm Hg. At this temperature sublimation of all of the boron took place in about 20 minutes and the aluminum disk took on a barely perceptible brownish color.

The Pu$^{239}$ source used for calibration was deposited on a platinum disk 0.375 inch in diameter. The average area density was determined to be less than 1 microgram per square centimeter by measuring the counting rate.

Gas Purification

Impurities commonly found in commercially available argon are nitrogen, oxygen, hydrogen, carbon dioxide, and water vapor. Colli and Facchini$^{16}$ demonstrated the ability of a calcium-magnesium alloy which was composed of 10 percent magnesium and maintained at a temperature of 450°C to relatively rapidly combine with the impurity gases listed above. In the present work purification of the counting gas was achieved by continuous circulation of the gas between the purifier shown in Fig. 7 and the
FIG. 7. GAS PURIFIER
ionization chamber. The purifier was made from stainless steel tubing with an outside diameter of 3.5 inches and having a wall thickness of 0.083 inch. The tubing was welded (A) to an endplate made from stainless steel stock 0.375 inch thick which served as the base of the purifier. The top of the purifier was silver soldered to a flange made from brass stock 0.5 inch thick. An endplate, also made from brass stock 0.5 inch thick, was secured to the flange with 8 steel machine bolts (H). A Teflon gasket (B) effected the vacuum seal. The purifier was attached to the chamber with copper tubing (E) and a short section of stainless steel tubing (C). A section one inch in length of the stainless steel tubing was machined to a wall thickness of 0.025 inch to minimize heat conduction. Heat was supplied to the purifier by means of heater wire (F) wound around the outside of the purifier, insulated from the steel walls with ceramic beads, and covered with several layers of asbestos (G). The temperature of the steel wall was measured by means of a thermocouple not shown in the figure. The Teflon gasket was cooled by the continuous circulation of water through copper tubing (D) which was soldered to the outside of the purifier. The purifying material was placed in a container which could be removed from the purifier for loading. The container was made of stainless steel and was fitted with spacers (I,K) to prevent packing of the purifying material. A piece of tapered copper pipe in the bottom (J) forced the circulating chamber gas to pass through the purifying material. This pipe was covered with a copper screen (L) to prevent the purifying material from blocking the opening.

The calcium-magnesium alloy used as the purifying material was obtained from the metallurgy division of the Ames Laboratory of the Atomic Energy Commission. The two metals were doubly distilled and the alloy was made in an argon atmosphere. Lathe turnings of the alloy were placed in an argon atmosphere as they were machined. The purifier container was loaded with alternate layers of the turnings and Pyrex glass wool.

After the container was loaded and placed in the purifier, the chamber was attached to a filling system for evacuating and outgassing. During outgassing the ionization chamber walls were maintained at a temperature of 800°C and the purifier at a temperature of 600°C until the pressure in the filling system was reduced to less than 0.004 micron Hg. The chamber and purifier were allowed to cool to room temperature before admitting gas into the chamber. During outgassing the calcium-magnesium alloy became molten and spread over the glass wool, considerably increasing the active surface area.

Certain operational characteristics of the ionization chamber were observed to be dependent on the purity of the counting gas. These were the rise time of pulses from the chamber, saturation voltages, and
Colli and Facchinin were able to show that as little as 0.1 percent of a molecular gas such as nitrogen in argon had a marked effect on the drift velocity of free electrons. These authors published curves constructed from their own data and data of other investigators in which the drift velocity of electrons in argon was plotted as a function of the ratio of field to pressure. Curves were given for nitrogen concentrations of 0.0, 0.1, and 1.0 percent. Calculations made from these curves indicated that the rise times for Pu\(^{239}\) alpha particle pulses should vary from 1.5 to 4.0 microseconds. The rise times of pulses appearing at the output of the first loop of the main amplifier were observed on a type 303-A Dumont cathode-ray oscillograph. The combined rise time of the preamplifier and the first loop of the main amplifier was observed to be about one microsecond. With commercial argon gas at a pressure of three atmospheres in the chamber, pulses due to Pu\(^{239}\) alpha particles were observed to have rise times ranging from 1.5 to 2.5 microseconds. After 24 hours with the purifier at a temperature 450°C, the rise times observed varied from 1.5 to 4.0 microseconds. When one percent of either carbon dioxide or nitrogen was added to the argon, the rise time of all pulses observed was about one microsecond.

Multiplication curves for the three gas mixtures used in this experiment are shown by Figs. 8-10. To obtain the data for these curves, the analyzer and amplifier were adjusted so that the plutonium alpha particle distribution was spread over the ten channels. The width of the distribution at half-maximum, as obtained on the pulse height analyzer, was about 2.5 channels. A median was calculated for each distribution and this median value was taken to be the position of the most probable alpha ionization. Each distribution contained about 1200 counts. The ratio of electric field to pressure in the grid-source region of the ionization chamber (E\(_{gs}\)/P) was maintained at a constant value and the median pulse height of the plutonium alpha particle distribution was obtained as a function of the ratio of the electric field to pressure in the grid-collector region of the chamber (E\(_{gc}\)/P). Fig. 8 shows a multiplication curve obtained with purified argon at two different gas pressures. Multiplication was observed to start at an E\(_{gc}\)/P value of 1.8. A change of 0.2 percent was considered significant and is indicated by an arrow in the figure. With commercial argon gas in the chamber, the pulse height was observed to fall with increasing E\(_{gc}\)/P before the start of multiplication. As the argon was purified, this decrease in pulse height disappeared. This phenomenon was probably due to the resonant capture of electrons by some electronegative gas such as oxygen. For the purification of argon, the outer wall of the purifier was maintained at a temperature of 440°C. The ability of the purifier to remove oxygen, nitrogen, and carbon dioxide at this temperature was tested by adding small amounts of these impurities to the argon gas in the chamber.
Δ 3 ATMOSPHERES PRESSURE; $E_{gc}/P = 0.18$ VOLTS/cm/mm OF Hg
O 2 ATMOSPHERES PRESSURE; $E_{gc}/P = 0.16$ VOLTS/cm/mm OF Hg

**FIG. 8. MULTIPLICATION CURVE FOR PURIFIED ARGON GAS.**
O 3 ATMOSPHERES; $E_{gc}/P = 0.19$ VOLTS/cm/mm OF Hg
MIXTURE OF COMMERCIAL GASES PURIFIED AT 200°C FOR 7 DAYS

Δ 2.2 ATMOSPHERES; $E_{gc}/P = 0.16$ VOLTS/cm/mm OF Hg
ARGON PURIFIED AT 440°C FOR 26 HRS. BEFORE ADDING N₂
MIXTURE PURIFIED AT 200°C FOR 19.5 HRS.

□ 2.2 ATMOSPHERES; $E_{gc}/P = 0.19$ VOLTS/cm/mm OF Hg
SAME MIXTURE PURIFIED AT 200°C FOR 43.5 HRS.

FIG. 9. MULTIPLICATION CURVES FOR ARGON GAS + 2% NITROGEN
3 ATMOSPHERES; $E_{gc}/P = 0.19$ VOLTS/cm/mm OF Hg.
MIXTURE OF COMMERCIAL GASES PURIFIED AT 200°C FOR 3 DAYS.

2 ATMOSPHERES; $E_{gs}/P = 0.16$ VOLTS/cm/mm OF Hg.
ARGON PURIFIED AT 440°C FOR 37 HRS. BEFORE ADDING CO$_2$
MIXTURE PURIFIED AT 200°C FOR 28 HRS.

FIG. 10. MULTIPLICATION CURVES FOR ARGON GAS + 5% CARBON DIOXIDE
small amount, 0.03 atmosphere, of either nitrogen or carbon dioxide was removed from 3 atmospheres of argon in 24 hours. Enough oxygen to decrease the pulse height of plutonium alpha particle pulses to 0.2 of their initial value was removed in 30 minutes. The same amount of oxygen was removed in 2.5 hours with the purifier at 200°C. At this temperature nitrogen and carbon dioxide were not removed over periods of several weeks.

The argon-nitrogen and argon-carbon dioxide gas mixtures were prepared using two different methods. In the first method the chamber was filled with the desired mixture of commercial gases. The mixture was then purified for several days with the purifier at a temperature of 200°C. In the second the chamber was filled with argon which was then purified at a temperature of 440°C for 24 hours. Nitrogen or carbon dioxide was then added to the argon and the mixture purified for several days with the purifier at 200°C.

Multiplication was not observed in argon-carbon dioxide and argon-nitrogen mixtures for the \( E_{\text{gc}}/P \) values obtainable with the ionization chamber used for this experiment. The decrease of pulse height with increasing \( E_{\text{gc}}/P \) for plutonium alpha particle pulses was observed in both gas mixtures. This effect was removed with purification in the argon-nitrogen mixture, as shown in Fig. 9. The magnitude of the effect decreased with purification in the argon-carbon dioxide mixture but was not eliminated. This is shown in Fig. 10. This phenomenon was also observed in argon-carbon dioxide gas mixtures by Herwig and Miller\(^9\).

Saturation curves for plutonium alpha particles were obtained for each gas mixture and are shown in Figs. 11-14. To obtain data for these curves, \( E_{\text{gc}}/P \) was maintained at a constant value and the median pulse height of the plutonium alpha particle distribution was obtained as a function of \( E_{\text{gc}}/P \). The breaks in the curves were the result of the capture of electrons by the grid wires. The minimum ratio of fields, \( E_{\text{gc}}/E_{\text{gg}} \), necessary to prevent electron capture is indicated for each gas mixture. No change in the saturation curves with purification was noted. Saturation curves were also obtained for the lithium recoil particles in each gas mixture and are shown in Fig. 15. Saturation was not indicated in purified argon. This phenomenon will be discussed in a later section.

**Background Reduction**

The ionization chamber used in this work was designed to eliminate an intolerable background counting rate observed by this investigator when a larger cylindrical ionization chamber was placed in a large slow neutron flux. These background pulses completely obscured the lithium recoil pulses and were shown to be due to the pile up of very small
FIG. II SATURATION CURVES AND MINIMUM RATIO OF FIELDS FOR PURIFIED ARGON GAS AT 3 ATMOSPHERES PRESSURE
FIG 12 SATURATION CURVES AND MINIMUM RATIO OF FIELDS FOR PURIFIED ARGON GAS AT 2 ATMOSPHERES PRESSURE
FIG. 13 SATURATION CURVES AND MINIMUM RATIO OF FIELDS FOR ARGON GAS + 2% NITROGEN
FIG. 14. SATURATION CURVES AND MINIMUM RATIO OF FIELDS FOR ARGON GAS + 5% CARBON DIOXIDE.
$E_g c / P = 1.7; 3 \text{ ATMOSPHERES}$

ARGON GAS + 5% CARBON DIOXIDE

$E_g c / P = 2.0; 3 \text{ ATMOSPHERES}$

ARGON GAS + 2% NITROGEN

$E_g c / P = 2.3; 2.6 \text{ ATMOSPHERES}$

FIG. 15. $L_i^7$ SATURATION CURVES
pulses. Kinsey and Bartholomew\textsuperscript{17} measured the neutron capture gamma ray spectrum from copper and zinc. They found most of the gamma rays from copper to have energies between 7 and 8 Mev and most of those from zinc to have energies between 5 and 8 Mev. These gamma ray energies are well above the threshold for pair production. Thus, a large number of very energetic electrons were present in the chamber whenever the chamber was placed in a large slow neutron flux. The number of background pulses was minimized in the new chamber by making the active volume small, the collection time for electrons short, and by using aluminum electrodes which have a low cross section for pair production. The parallel-plate design was used rather than the cylindrical design for the ionization chamber so that shorter collection time for electrons could be achieved.

RESULTS

Figs. 16-19 show ionization distribution curves for plutonium alpha particles, alpha particles from the reaction $^\text{B}_{10}(n,\alpha)Li^7\ast$, and the excited lithium recoils in various gases. The gases used were purified argon, argon plus nitrogen, and argon plus carbon dioxide. Calibration curves for each distribution are also shown. Each calibration curve consisted of four points through which a straight line was visually drawn. Two points were obtained before and two after recording the data for each distribution to detect amplifier drift. Fig. 16 and Fig. 17 show the variation in the resolution of the equipment corresponding to main amplifier time constants of 10 and 5 microseconds respectively.

Fig. 20 consists of eight pages of tables which summarize the data and calculations comparing the apparent energies of the alpha particles and lithium recoils from the reaction $^\text{B}_{10}(n,\alpha)Li^7\ast$ as obtained in the various gas mixtures. These tables contain the information relative to the experimental conditions, the most probable particle ionizations, the ratios of the most probable ionizations, and the apparent particle energies.

For this experiment, the energy of the $^{239}\text{Pu}$ alpha particles was taken to be $5.147 \pm 0.004$ Mev. Asaro and Perlman\textsuperscript{16}, using a magnetic alpha particle spectrograph, analyzed the complex alpha spectrum of $^{239}\text{Pu}$. They found the spectrum to consist of three groups with energies of $5.150 \pm 0.002$, $5.137 \pm 0.002$ and $5.100 \pm 0.002$ Mev and relative intensities of 69, 20, and 11 percent respectively. These energies were too close together to be resolved in the ionization chamber. The position of the peak of the ionization distribution curve for $^{239}\text{Pu}$ alpha particles was probably not affected by the presence of the low energy group. The mean energy of the other two groups weighted according
FIG. 16. IONIZATION DISTRIBUTION AND CALIBRATION CURVES IN PURIFIED ARGON GAS AT 2.6 ATMOSPHERES
FIG. 17. IONIZATION DISTRIBUTION AND CALIBRATION CURVES IN PURIFIED ARGON GAS AT 2.6 ATMOSPHERES
FIG. 18. Ionization distribution and calibration curves in argon gas + 2% nitrogen at 2.2 atmospheres.
FIG. 19. IONIZATION DISTRIBUTION AND CALIBRATION CURVES IN ARGON GAS + 5% CARBON DIOXIDE AT 2.3 ATMOSPHERES
FIG. 29a  EXPERIMENTAL CONDITIONS AND MOST PROBABLE ALPHA AND LITHIUM IONIZATIONS IN
PURIFIED ARGON GAS

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Press.</th>
<th>$E_{ac}/p$</th>
<th>$E_{ag}/p$</th>
<th>RC's (μsec.)</th>
<th>$^{239}\text{Pu}-\alpha$</th>
<th>$^{10}\text{B}-\alpha$</th>
<th>$^{7}\text{Li}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>2.9</td>
<td>1.9</td>
<td>0.51</td>
<td>10</td>
<td>790.7</td>
<td>225.7</td>
<td>118.5</td>
</tr>
<tr>
<td>1</td>
<td>2.8</td>
<td>2.1</td>
<td>0.50</td>
<td>10</td>
<td>783.5</td>
<td>224.7</td>
<td>119.6</td>
</tr>
<tr>
<td>2</td>
<td>2.8</td>
<td>2.1</td>
<td>0.54</td>
<td>10</td>
<td>787.1</td>
<td>224.9</td>
<td>118.7</td>
</tr>
<tr>
<td>8</td>
<td>2.6</td>
<td>2.3</td>
<td>0.58</td>
<td>10</td>
<td>795.9</td>
<td>227.3</td>
<td>120.3</td>
</tr>
<tr>
<td>9</td>
<td>2.6</td>
<td>2.3</td>
<td>0.58</td>
<td>5</td>
<td>766.1</td>
<td>213.6</td>
<td>117.4</td>
</tr>
<tr>
<td>17</td>
<td>2.4</td>
<td>2.5</td>
<td>0.65</td>
<td>10</td>
<td>819.5</td>
<td>233.4</td>
<td>124.5</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>820.3</td>
<td>233.5</td>
<td>124.1</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>820.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2.0</td>
<td>2.5</td>
<td>0.70</td>
<td>10</td>
<td>806.8</td>
<td>232.2</td>
<td>123.1</td>
</tr>
<tr>
<td>13</td>
<td>2.0</td>
<td>2.1</td>
<td>0.54</td>
<td>10</td>
<td>793.8</td>
<td>225.8</td>
<td>120.4</td>
</tr>
<tr>
<td>10</td>
<td>1.9</td>
<td>3.2</td>
<td>0.83</td>
<td>10</td>
<td>844.2</td>
<td>241.7</td>
<td>131.2</td>
</tr>
<tr>
<td>20</td>
<td>1.1</td>
<td>2.4</td>
<td>0.60</td>
<td>10</td>
<td>223.4</td>
<td>119.7</td>
<td>120.0</td>
</tr>
<tr>
<td>Run No.</td>
<td>Press. (atms.)</td>
<td>$E_{239\alpha}/P$</td>
<td>$E_{10\alpha}/P$</td>
<td>RC's (μsec.)</td>
<td>Most Probable Ionization (Arbitrary Units)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>---------------</td>
<td>----------------</td>
<td>----------------</td>
<td>-------------</td>
<td>-----------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.0</td>
<td>4.2</td>
<td>1.08</td>
<td>10</td>
<td>Pu$^{239\alpha}$ $^{(E_{10\alpha})}$ Li$^{7\alpha}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.55</td>
<td>2.3</td>
<td>0.60</td>
<td>10</td>
<td>221.3  117.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>219.8  117.6</td>
<td></td>
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</tr>
</tbody>
</table>
### FIG. 20b RATIOS OF MOST PROBABLE IONIZATIONS, AND CALCULATED ENERGIES IN ARGON GAS

<table>
<thead>
<tr>
<th>Run No.</th>
<th>$I_{(B-\alpha)}/I_{Pu-\alpha}$</th>
<th>$I_{Li7e}/I_{Pu-\alpha}$</th>
<th>$E'_{(B-\alpha)0}$ (MeV)</th>
<th>$E'_{Li7e}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.2854</td>
<td>0.1499</td>
<td>1.469</td>
<td>0.772</td>
</tr>
<tr>
<td>1</td>
<td>0.2850</td>
<td>0.1517</td>
<td>1.467</td>
<td>0.781</td>
</tr>
<tr>
<td>2</td>
<td>0.2857</td>
<td>0.1508</td>
<td>1.470</td>
<td>0.776</td>
</tr>
<tr>
<td>8</td>
<td>0.2856</td>
<td>0.1537</td>
<td>1.470</td>
<td>0.791</td>
</tr>
<tr>
<td>9</td>
<td>0.2853</td>
<td>0.1533</td>
<td>1.468</td>
<td>0.785</td>
</tr>
<tr>
<td>17</td>
<td>0.2847</td>
<td>0.1516</td>
<td>1.465</td>
<td>0.780</td>
</tr>
<tr>
<td>14</td>
<td>0.2878</td>
<td>0.1526</td>
<td>reject</td>
<td>0.781</td>
</tr>
<tr>
<td>13</td>
<td>0.2845</td>
<td>0.1517</td>
<td>1.464</td>
<td>reject</td>
</tr>
<tr>
<td>10</td>
<td>0.2863</td>
<td>0.1554</td>
<td>1.474</td>
<td>reject</td>
</tr>
<tr>
<td>Averages</td>
<td></td>
<td></td>
<td>1.468</td>
<td>0.782</td>
</tr>
<tr>
<td>Standard Deviations of Averages</td>
<td></td>
<td></td>
<td>±.0021</td>
<td>±.0038</td>
</tr>
<tr>
<td>Run No.</td>
<td>$I_{(B-\alpha_1)}/I_{Pu-\alpha}$</td>
<td>$I_{Li^{7+}}/I_{(B-\alpha_1)*}$</td>
<td>$E_{Li^{7+}}$ (Mev)</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------</td>
<td>---------------------------------</td>
<td>------------------</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.5365</td>
<td></td>
<td>0.788</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.5350</td>
<td></td>
<td>0.785</td>
<td></td>
</tr>
<tr>
<td>Average</td>
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<td></td>
<td>0.787 ± 0.0045</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.5323</td>
<td></td>
<td>0.781 ± 0.0056</td>
<td></td>
</tr>
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</table>
FIG. 20e EXPERIMENTAL CONDITIONS AND MOST PROBABLE ALPHA AND LITHIUM IONIZATION

<table>
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<tr>
<th>Run No.</th>
<th>Press. (atms.)</th>
<th>Egc/P</th>
<th>Egs/P</th>
<th>RC's (μsec.)</th>
<th>Most Probable Ionization (Arbitrary Units)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pa²³³α</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(40-α)*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Li7*</td>
</tr>
<tr>
<td>A 5% CO₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.9</td>
<td>1.7</td>
<td>0.38</td>
<td>10</td>
<td>804.9</td>
</tr>
<tr>
<td>4</td>
<td>2.9</td>
<td>1.7</td>
<td>0.38</td>
<td>10</td>
<td>805.2</td>
</tr>
<tr>
<td>18</td>
<td>2.3</td>
<td>2.2</td>
<td>0.60</td>
<td>5</td>
<td>776.8</td>
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<tr>
<td>15</td>
<td>2.1</td>
<td>2.4</td>
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<td>779.0</td>
</tr>
<tr>
<td>19</td>
<td>1.0</td>
<td>2.7</td>
<td>0.78</td>
<td>5</td>
<td>785.6</td>
</tr>
<tr>
<td>A 2% H₂</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3.0</td>
<td>2.0</td>
<td>0.49</td>
<td>10</td>
<td>778.7</td>
</tr>
<tr>
<td>6</td>
<td>3.0</td>
<td>2.0</td>
<td>0.53</td>
<td>10</td>
<td>785.2</td>
</tr>
<tr>
<td>7</td>
<td>2.9</td>
<td>2.0</td>
<td>0.53</td>
<td>10</td>
<td>785.6</td>
</tr>
<tr>
<td>Run No.</td>
<td>Press. (atms.)</td>
<td>$E_{EC}/P$</td>
<td>$E_{ES}/P$</td>
<td>RC's ($\mu$sec.)</td>
<td>Pu$^{239}$ (Arbitrary Units)</td>
</tr>
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<td>--------</td>
<td>----------------</td>
<td>-----------</td>
<td>-----------</td>
<td>------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>16</td>
<td>2.2</td>
<td>2.4</td>
<td>0.73</td>
<td>5</td>
<td>765.8</td>
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<td></td>
<td></td>
<td></td>
<td>766.1</td>
</tr>
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</table>
### FIG. 20d
RATIOS OF MOST PROBABLE IONIZATIONS, AND CALCULATED ENERGIES

<table>
<thead>
<tr>
<th>Run No.</th>
<th>$I_{(B-\alpha)}/I_{Pu-\alpha}$</th>
<th>$I_{L17c}/I_{Pu-\alpha}$</th>
<th>$E'_{(B-\alpha)}$ (Mev)</th>
<th>$E'_{L17c}$ (Mev)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A + 5% CO₂</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.2804</td>
<td>0.1496</td>
<td>1.443</td>
<td>0.770</td>
</tr>
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<td>0.2803</td>
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</tr>
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<td>0.2806</td>
<td>0.1507</td>
<td>1.444</td>
<td>0.776</td>
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<td>15</td>
<td>0.2809</td>
<td>0.1519</td>
<td>1.446</td>
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<td>Average</td>
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<td>1.444</td>
<td>0.774</td>
</tr>
<tr>
<td><strong>A + 2% H₂</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.2857</td>
<td>0.1536</td>
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<td>0.791</td>
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<td>0.1513</td>
<td>1.450</td>
<td>0.779</td>
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<td>0.780</td>
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<td>0.2837</td>
<td>0.1527</td>
<td>1.460</td>
<td>0.786</td>
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<td>Average</td>
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<td>0.784</td>
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<td>Combined Standard Deviations</td>
<td>± 0.0018</td>
<td>± 0.0016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run No.</td>
<td>$\frac{T(B-\alpha)}{T_{Pu-\alpha}}$</td>
<td>$E_{\alpha}(\text{MeV})$</td>
<td>$A+5%\text{ CO}_2$</td>
<td></td>
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<tr>
<td>--------</td>
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<td></td>
</tr>
<tr>
<td>19</td>
<td>0.5466</td>
<td>0.789 ± 0.0023</td>
<td>19</td>
<td></td>
</tr>
</tbody>
</table>
to intensities is 5.147 Mev.

The energies for the alpha particles and the excited lithium recoils from the reaction $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ were taken to be $1.473 \pm 0.002$ and $0.841 \pm 0.002$ Mev respectively as calculated by Rhodes et al. from independent data.

**DISCUSSION**

Fig. 21 shows a comparison of the apparent energy values for the alpha particles and for the lithium recoils from the reaction $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ as obtained from the most probable ionizations of the present experiment with those obtained from ionization chamber experiments by other investigators. The uncertainties quoted for the present experiment are the standard deviations of the average values as calculated from the data taking into account the uncertainty in the energy for the plutonium alpha particles. The energy values obtained in the argon-carbon dioxide gas mixture are in good agreement with those obtained by Hanna and by Rhodes, Franzen, and Stephens. The value obtained for the boron alpha particles in purified argon agrees with that obtained by Jesse, Forstat, and Sadauskis. The value obtained for the lithium recoils is in serious disagreement with the value obtained by the latter investigators.

Wilcox measured the rate of energy loss for alpha particles and for $^{6}\text{Li}$ nuclei in gold. The measurements were carried out for alpha particles ranging in energy from 30 kev to 1400 kev and for the $^{6}\text{Li}$ nuclei from 750 kev to 850 kev. Calculations made from these data give a value of $1.17 \pm 0.08$ for the ratio of the rate of energy loss for 800 kev $^{6}\text{Li}$ nuclei to the rate of energy loss for 1400 kev alpha particles in gold. Although Wilcox's data were shown to be in error by Warshaw, the expected correction is less than the uncertainty indicated above. Rhodes et al. in their measurements on the $^{10}\text{B}(n,\alpha)^{7}\text{Li}$ reaction used a thick boron source and corrected for the source thickness by fitting calculated distribution curves to their measured ionization distributions. They obtained a best fit by assuming an equivalent layer of 55 kev for the alpha particles and 64 kev for the lithium recoils. This would give a value of 1.16 for the ratio of the rates of energy loss in boron. If the assumption is made that the 5 kev ionization defect measured in purified argon in this experiment is the result of source thickness, then the value obtained for the lithium recoil can be increased by about 6 kev. If the uncertainty in the measurement of 4 kev is added to this value, about 50 kev of energy are left which did not appear as ionization.

Serious objection may be raised to the saturation curve obtained for the lithium recoils in purified argon. This curve would seem to
FIG. 21 ENERGIES OF ALPHA PARTICLES AND LITHIUM RECOILS AS MEASURED IN IONIZATION CHAMBERS BY VARIOUS INVESTIGATORS (MEV)

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Hanna</th>
<th>Rhodes</th>
<th>Jesse</th>
<th>This Experiment</th>
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<tr>
<td></td>
<td></td>
<td>Fransen</td>
<td>Forstat</td>
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<td></td>
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<td>Stephens</td>
<td>Edeuskis</td>
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Gas Mixtures

<table>
<thead>
<tr>
<th></th>
<th>Hanna</th>
<th>Rhodes</th>
<th>Jesse</th>
<th>This Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>1.471 ± 0.006$^b$</td>
<td>1.468 ± 0.002</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.839 ± 0.004$^b$</td>
<td>0.782 ± 0.004</td>
<td></td>
</tr>
<tr>
<td>$H_2$</td>
<td></td>
<td>1.460 ± 0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A + H_2$</td>
<td>0.784 ± 0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A + CO_2$</td>
<td>1.431 ± 0.013</td>
<td>1.444 ± 0.010</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.777 ± 0.008</td>
<td>0.769 ± 0.006</td>
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</tr>
</tbody>
</table>

$^b$Computed from the measured reaction energy of 2.310 ± 0.010 MeV assuming the same energy per ion pair for the alpha particles and the lithium recoils from the reaction as for the polonium alpha particles used in the calibration.
indicate that the low value for the ionization obtained for these particles was due to ion recombination. The probability for ion recombination increases as the average density of ionization along the track increases and is an inverse function of the ratio of electric field to gas pressure. Thus, the probability decreases with decreasing pressure for a constant ratio of field to pressure. Measurements were made on the ionization produced by the alpha particles and lithium recoils in purified argon at pressures of 1 and 0.5 atmosphere, Fig. 20a. The energy for the lithium recoils was then calculated assuming a value of 1.468 Mev for the energy of the alpha particles, Fig. 20b. The expected increase for the measured energy of the lithium recoils was not observed. This would seem to indicate that ion recombination was not occurring.

If the value for the ionization defect for the lithium recoils in purified argon obtained by this experiment is assumed to be correct, there would seem to be a basic difference between electron collection and total ion collection. One such difference might be due to the metastable state of argon. The ratio of excitation to ionization might be expected to be greater for the lithium recoils than for the alpha particles. The resulting metastable states could conceivably be discharged by collisions with the source plate resulting in ionization which would not be measured using electron collection due to the time required. This might also account for the poor saturation curves obtained for the lithium recoils.

Juren and Rosenwasser measured the ratio of the ionization produced by the lithium recoils to that produced by the alpha particles from the reaction $^{10}\text{Be}(n,\alpha)^{7}\text{Li}$ in various concentrations of carbon dioxide in argon and at various pressures. Their results show an increase in the ratio with decreasing carbon dioxide concentration and with decreasing pressure. It should be pointed out that their data were obtained from integral curves and are thus subject to considerable uncertainty. One set of three determinations of this ratio was made in an argon-carbon dioxide gas mixture at a pressure of one atmosphere to check this phenomenon, Figs. 20c,d. A small increase in the energy as measured for the lithium recoils was noted but not to the extent expected from the data of these investigators.
CONCLUSIONS

The ionization yields for the alpha particles and the excited lithium recoils from the reaction $^7B(n,\alpha)Li^{7*}$ were measured in purified argon, argon plus 2 percent nitrogen, and argon plus 5 percent carbon dioxide. The results of this experiment along with those of Facchini et al\(^7\) on the alpha particles from the reaction $^6Li(n,\alpha)H$, Jesse and Sadauskis \(^{10,11}\) on the alpha particles from samarium, and Jesse et al\(^5\) on alpha particles from other natural alpha emitters demonstrate the constancy of $W$ for alpha particles in argon above an energy of 1.4 Mev. Further, ionization defects of $8 \pm 3$ and $24 \pm 3$ kev were measured for the alpha particles from the reaction $^7B(n,\alpha)Li^{7*}$ in argon plus nitrogen and in argon plus carbon dioxide respectively. These results show the existence of a molecular defect for low energy alpha particles in the presence of polyatomic gases as suggested by the measurements of Herwig and Miller\(^9\) on fission fragments.

An ionization defect of about 50 kev was measured for the lithium recoils in purified argon gas. This value is subject to considerable uncertainty due to conflicting evidence on the existence of ion recombination. This evidence would seem to indicate that there may be a fundamental difference between electron collection and total ion collection not as yet understood. An experiment designed to measure the ionization yield of low energy positive ions in various gases using both electron collection and total ion collection in the same chamber would be of particular interest. Ionization defects of $51 \pm 3$ and $61 \pm 3$ kev were measured for the lithium recoils in argon plus nitrogen and in argon plus carbon dioxide respectively. The portion of each defect which may be attributed to the presence of a polyatomic gas can not be obtained from this experiment.


