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INSTRUMENTATION FOR ENERGY DETERMINATION OF HIGH ENERGY HEAVY PARTICLES

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INSTRUMENTATION FOR ENERGY DETERMINATION
OF HIGH ENERGY HEAVY PARTICLES

Richard L. Shuey

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I. INTRODUCTION

An excellent summary of the information published prior to 1946 about the fission process is given in a well-referenced book by Stephens. Since that date many papers have appeared in the literature reporting new and recently declassified work. This report describes an experimental investigation of the kinetic energies of the fragments resulting from spontaneous fission.

The mass and energy distributions of fragments from neutron induced fission have been investigated by Jentschke and others. It has been established by chemical means that the fragment mass number versus yield follows roughly the curve of Fig. 1. It is important to note that chemical methods analyze the disintegration products of the fragments, not the fragments existing at the moment of fission. As the bombarding neutron energy or the atomic number of the fissioning material is increased the valley shown in Fig. 1 becomes less pronounced. If the neutron energy is sufficiently large the curve becomes single-peaked.

Analysis of ionization chamber pulses from slow neutron fission yields the curve of Fig. 2. The dependence on atomic number and neutron energy is roughly the same as for the mass distribution, Fig. 1. Experiments with both fragments give a total energy curve like Fig. 3. As the nucleus mass increases the total energy liberated in fission also increases. Three dimensional plots of probability and the energy of both fragments for spontaneous and slow neutron fission will be discussed in a later section.
Fig. 1. Mass Number vs. Fission Yield for U\textsuperscript{235} Slow Neutron Fission.

Fig. 2. Energy vs. Fission Yield for U\textsuperscript{235} Slow Neutron Fission.

Fig. 3. Total Energy vs. Fission Yield for U\textsuperscript{235} Slow Neutron Fission.
Fig. 1

Fig. 2

Fig. 3
Spontaneous fission rates have been studied by Petrjak\textsuperscript{26} and others.\textsuperscript{26-34} Some equipment considerations for such experiments are given in this report. Spontaneous fission fragment energies have been studied by Wiegand and Segre,\textsuperscript{24} a group at Chalk River,\textsuperscript{25} and Whitehouse and Galbreith.\textsuperscript{58} The results differ but slightly from those of the slow neutron case, Fig. 2. The investigation described in this report considers both fragments simultaneously.

II. EQUIPMENT

The principal non-chemical methods of studying fission fragments are: (a) stacked thin films,\textsuperscript{35} (b) cloud chambers,\textsuperscript{36} (c) ionization chambers,\textsuperscript{2} (d) photographic emulsions,\textsuperscript{32} and (e) calorimeter measurements.\textsuperscript{6} In the work covered by this report ionization chambers were used. A photographic method was used to measure the magnitudes of the pulses from the ionization chambers.

A general block diagram of the equipment used is shown in Fig. 4. As indicated in the figure, the equipment consists of a double ionization chamber and its associated electronics. Let us follow through on the block diagram the effects of a fission fragment in one side of the ionization chamber. Later detailed discussion will concern primarily those approaches, techniques and methods that are either new or not generally known.

A sample is mounted on a thin film in the center of the cathode: see Fig. 4. Conservation of momentum requires that the fragments resulting from a binary fission go in approximately opposite directions. Throughout this report a binary fission will be taken as a nucleus splitting into two major fragments and possibly prompt neutrons and alpha-particles. The small effects of prompt neutrons, alpha-particles, and gamma-rays on the momentum balance will not be considered. A fission fragment is stopped in the cathode (source)-grid region. While being stopped it ionizes molecules of the gas filling
Fig. 4. General Block Diagram of Double Ionization Chamber and Associated Equipment.
the chamber. The electrons resulting from this ionization are collected on the plate (collector) and constitute a current into the input of the preamplifier. The number of electrons is very nearly proportional to the energy of the fission fragment. The voltage developed by these electrons across the input capacity of the preamplifier is thus proportional to energy. The output pulse of the preamplifier is clipped by a pulse forming network (PFN). One of the amplifier outputs is fed through a length of RG-65U delay cable to the vertical deflection plates of a synchroscope. The other output is fed to a discriminator. If the input to the discriminator exceeds a fixed value the output provides a synchronization pulse. The synchronization pulse: (a) intensifies the cathode ray tube; (b) initiates the synchroscope sweep; (c) trips a scaler and (d) advances the film in the camera. The photographed deflection of the cathode ray tube sweep is proportional to the fission fragment energy. As all equipment is duplicated for the other side of the chamber both fragment energies are determined simultaneously.

A. Ionization Chambers

Rossi and Staub have published an excellent comprehensive book on ionization chambers and counters. Deviating from their analysis of induced charge let us consider the induced current. This is an approach commonly used by vacuum tube engineers. It is not a more basic approach than that of induced charge. In fact, the current theorem involved is usually derived from Green's reciprocity theorem or from Green's integral theorem. The method does, however, result in a simplified viewpoint of certain phenomena and circuit problems. Ramo has shown that if there are n conducting bodies fixed in space the current induced in the i th conductor by a moving charge \( q \) is given by equation 1 (see Fig. 5).
Fig. 5. Theorem on the Current Induced in a Fixed Conductor due to a Moving Charge.
WHERE \( E_a \) = FIELD AT Q WITH ALL CONDUCTORS BUT 1 GROUNDED AND ONE VOLT ON 1.

\[ I_i = q \vec{v} \cdot \vec{E}_a \]

\( \vec{V} \) = VELOCITY OF Q

FIG. 5
(1) \( i = Q \bar{v} \bar{E}_a \)

\( i \) = current induced in \( i \)th conductor
\( Q \) = charge
\( \bar{E}_a \) = field at \( Q \) if one volt placed on \( i \) and all other conductors grounded
\( \bar{v} \) = velocity of \( Q \)

MKS units

The application of this theorem to counters suggests that all gas ionization counters be considered as current sources. This includes Geiger and proportional counters as well as ionization chambers.

Consider a parallel plate ionization chamber, Fig. 6. The waveforms resulting from ionizing particles of equal energy but different paths are shown as case I and case II. Both particles form an equal number of electrons. Infinite plane conductors are assumed. Unfortunately, the chamber capacity integrates the induced current. Such a chamber is normally not used for energy measurements because of the dependence of the induced current integral on the path of the ionizing particle. However, the maximum value of the derivative of this integral is a measure of the ionizing particle's energy, i.e., the number of electrons formed. Figs. 7 and 8 indicate a method of making use of this fact. This system was tried crudely with alpha-particles and gave the expected waveforms. Sherr and Peterson\(^{39}\) have previously discussed some of the properties that such a chamber should have.

A parallel plate chamber operated as in Figs. 7 and 8 has several disadvantages. A constant electron velocity in the gas is required and can be obtained by using an argon and carbon dioxide mixture. Rossi and Staub\(^{37}\) give a curve showing the velocity versus field strength per unit pressure for such a mixture. A definite velocity plateau exists. From a practical standpoint, the requirement of a constant \( \bar{v} \bar{E}_a \) (see equation 1) demands that
Fig. 6. Parallel Plate Ionization Chamber, Theory. The figure shows the current induced in the collecting electrode due to electrons and the voltage across the collecting electrode.
HI VOLTS

CASE I
ALPHA IONIZATION

Qn

CASE II

C = CHAMBER AND INPUT GRID CAPACITY

R

\[ I = \sum_{i=1}^{n} Q_i \bar{V} \cdot \bar{E}_a \]

= \bar{V} \cdot \bar{E}_a \cdot \varepsilon Q_n

TIME

INDUCED CURRENT VS TIME

VOLTAGE

\[ \text{VOLS} = \int_{0}^{T} I \, dt \]

CHAMBER SIGNAL VOLTAGE VS TIME

MU 479

FIG. 6
Fig. 7. Differentiation-Integration Circuit.
The circuit shown is for use with a parallel plate ionization chamber. The output is proportional to the number of electrons formed and results in a very fast chamber.
DIFFERENTIATING NETWORK

PRE AMP
GAIN 30
VOLTAGE SOURCE

100 μF

AMPLIFIER
GAIN 30
CURRENT SOURCE

SHORTED LINE

TO AMPLIFIER, DISCRIMINATOR
SCOPE ETC.

MU 478

FIG. 7
Fig. 8. Waveforms of Differentiation-Integration Circuit. The waveforms of the circuit shown in Fig. 7 are indicated.
CHAMBER SIGNAL VOLTAGE = $V_s$

$T_R = \text{RISE TIME}$

$\frac{dV_s}{dt} \sim I$

$T_R$

CLIPPED $\frac{dV_s}{dt} = \left[ \frac{dV_s(t)}{dt} - \frac{dV_s(t-T_c)}{dt} \right]$

$T_c = \text{CLIPPING TIME}$

FIG. 8
both $\bar{v}$ and $\bar{E_a}$ be constant. The practice of using voltage dividing rings controls only $\bar{v}$. The $E_a$ term can be made constant by approaching infinite plane geometry. This dictates a chamber of large radius and results in a large capacity and poor signal to noise ratio.

The advantage of such a chamber is its short resolving time. The resolving time is limited by the formation time of the ions and this is of the order of $5 \times 10^{-9}$ seconds.

In measuring spontaneous fission rates the primary problem is to avoid the piling up of alpha pulses so that they look like fission pulses. If $n$ alpha pulses occur within the resolving time of the chamber, a pulse $n$ times higher than one alpha-particle will result. This requires chambers of short resolving time. Rossi and Staub\textsuperscript{37} give the counting rate of pulses $n$ times normal in magnitude resulting from pile ups as:

$$\begin{equation}
    c_n = \frac{n_o (\gamma n_o)^{n-1}e^{-\gamma n_o}}{(1 + \gamma n_o) ((n-1)!)^2} = \frac{K (\gamma n_o)^{n-1}}{(n-1)!}
\end{equation}
$$

In equation 2, $n_o$ is the average number of pulses per unit time, $K$ is a constant for any counter, and $\gamma$ is the pulse width. The equation is derivable from Poisson's law. In practice, rectangular pulses do not exist and the degree of coincidence required to register a pulse is not clear. However, calculations using an equivalent pulse width give satisfactory results. Taking the log of both sides of equation 2 and applying Stirling's approximation for the factorial gives:

$$\begin{equation}
    \ln c_n = \ln K + (n-1) \ln \gamma n_o - \ln (n-1)! \\
    = \ln K - \ln \gamma n_o + 1/2 \ln 2\pi + n(\ln \gamma n_o - \ln n) - 1/2 \ln n
\end{equation}
$$

The fourth term on the right hand side is the most important and is approximately linear.
As shown in Fig. 9 a fission bias curve is a plot of counting rate versus discriminator bias voltage. A given discriminator bias voltage represents a given energy. It follows that a fission bias curve may be taken as a plot of counting rate of pile-ups greater than a given energy versus that given energy. As expected from equation 3, Fig. 9 is a straight line.

Fig. 10 shows a chamber used for fission rate measurements. The spacing of the chamber is less than the range of a fission fragment and consequently less than half the range of an alpha-particle. The specific ionization of a fission fragment is greatest at the beginning of its path where that of an alpha-particle is smallest. These factors help provide a favorable fission signal to alpha noise ratio. The alpha pulses are reduced in size much more than the fission pulses. Thus, there are less alpha pile-ups for a bias setting that corresponds to a given fission energy. With argon and carbon dioxide the electron transit time of the chamber is 0.2 to 0.3 microseconds. The poor approximation to infinite plane geometry and close spacing result in an output not strictly proportional to fragment energy. Clipping times down to 0.05 microseconds have been used with this chamber. A clipping time this short is equivalent to differentiation.

The energy experiments in this report have been made using the parallel plate-grid chamber of Fig. 11. The high fission rate of Cm$^{242}$ does not require an extremely fast chamber. The grid shields the plate from the cathode-grid region. Thus, current is induced in the plate only by charged particles in the grid-plate region. The final value of the integrated plate current is a function only of the number of electrons, or ionizing particle energy. The design of the grid follows the theory of Bunemann and is such that all electrons reach the plate. The top seal is lead and the spacers ceramic. The feed-through insulators are of the kovar-glass type.
Fig. 9. Fission Bias Curve.
This fission bias curve was taken on the fission rate equipment. The points shown are representative points taken over a week's time.
FISSION BIAS CURVE
APPROXIMATELY $10^8 \text{ a c/m}
FISSION RATE EQUIPMENT

FISSION RATE

ALPHA PILE UPS

COUNTS / MIN.

BIAS VOLTS

MU 486

FIG. 9
Fig. 10. Fission Rate Ionization Chamber.
Fig. 11. Double Ionization Chamber.
The drawing shows a section view of the double ionization chamber. It is intended to show dimensions only. Electrical connections are shown in Fig. 4.
DOUBLE IONIZATION CHAMBER

FIG. II

MU 485

WASHER HOLD DOWN RING

LEAD WASHER

PLATE

GRID

CATHODE

GRID

PLATE

OMITTED FROM DWG:
INSULATORS
FEED THROUGH POINTS
SCREW HOLES
SPRING LOADED HOLD DOWN CLAMPS FOR RING
BRACKETS
HOLD DOWN CLAMPS FOR TOP

GRID CHARACTERISTICS:
6 MIL STAINLESS STEEL WIRE EVERY 50 MILS.

1 INCH
The solid dish-like electrodes tend to funnel the electrons through the grid. The chamber was checked with Am$^{241}$ plus Cm$^{242}$ alpha-particles. The resolving time of a grid chamber is limited by the electron transit time. With argon and carbon dioxide the rise time of the chamber is approximately 0.3 microsecond.

B. Counter Gas

The properties of counter gases have been investigated by Rossi$^{37}$ and others.$^{41-45}$ Following their work a mixture of 96 percent argon and 4 percent carbon dioxide was used. Commercial gases were mixed at this laboratory. This mixture provides a high electron drift velocity. As long as only metal, glass, and ceramic materials are used in a chamber, circulation of the gas is not necessary. An existing chamber with polystyrene insulation proved unsatisfactory. The fission rate measurements were taken with unpurified gas. The stability of the fission bias curve, Fig. 9, is an indication of the stability of the gas properties, at least for alpha-particles. It is worth noting that the carbon dioxide lowers the agitation energy of the electrons in the gas. The electrons lose energy by exciting the low energy levels in the carbon dioxide molecules. This should reduce the electron attachment.$^{44}$

Recent investigation has shown that at the high ionization intensity resulting from fission fragments electron attachment is very important.$^{44}$ It has been known for some time that recombination is more important with fission fragments than with alpha-particles. Of the expected impurities in tank argon, water and oxygen are the most troublesome. For this reason, the gas purifying system in Fig. 12 was installed for the energy measurements. The reducer was filled with copper oxide and heated to 200-250 degrees centigrade. Hydrogen was slowly passed through the system giving:

\[ \text{(4) } \text{CuO} + \text{H}_2 \longrightarrow \text{Cu} + \text{H}_2\text{O} \]
Fig. 12. Gas Purifier.
ASBESTOS

THERMOCOUPLE

HEATER

ASBESTOS

96% A + 4% CO₂
FROM TANK

RUBICON POTENTIOMETER

REDUCER CONTAINS HARSHAW CHEMICAL CORP COPPER CATALYST CODE 469-076

DRIER USES W.A. HAMMOND DRIERITE CO. COMERCIAL DRIER (Co₃S₂O₄)

GAS FILTER

FIG. 12

MU 492
After this reaction was complete the argon and carbon dioxide mixture was connected to the purifier. Oxygen is removed by the following reaction:

\[
(5) \quad 2\text{Cu} + \text{O}_2 \longrightarrow 2\text{CuO}
\]

The drier section utilizes a commercial drying agent. Slow neutron fission experiments with this arrangement gave satisfactory results. As the chamber voltage was increased a fairly flat plateau of fission pulse distribution was obtained. The slow neutron experiments were done with a polonium-beryllium neutron source. These tests were made on only one side of the chamber.

The motion of electrons in a gas is not completely understood. Electron velocity, recombination, electron attachment, etc., are affected by small quantities of impurities. It is known that impurities of one part per million are important. Although the mass spectrograph available, Consolidated Engineering Corporation type 21-102, does not have this accuracy, the gas was analyzed by this means. The differential pulse analyzer of the Radiation Laboratory is known to have better resolution when operated with purified gas. It was mainly in the hope of understanding this that the tests were made.

The analysis of commercial tank argon was as follows:

- argon $>99.917$ percent
- oxygen $<0.007$ percent
- nitrogen $<0.050$ percent
- water $<0.026$ percent

A check with Linde Air Products disclosed that tank argon is guaranteed 99.8 percent pure. The mixture of argon and carbon dioxide contained no further impurities. The outputs of three different filter systems like Fig. 12 were analyzed. All contained a greater amount of water than the original gas. The drier, which has a finite vapor pressure, was removed from the system for some runs. Later checks have not verified the above water analysis.
For this reason, the drier has been included in some of the later runs. The study of counting gases is continuing.

The average energy of the fission fragments is the same with or without drying and with or without gas circulation. This indicates that all methods are satisfactory. The amount of impurity present should determine the minimum voltage required across the chamber to prevent recombination. The slow neutron fission measurements indicated that this is 900-1200 volts. Data-taking runs were made with 1500 volts. The constancy of the average curium fragment energy indicates that the different operating conditions were above the minimum voltage required.

The gas conditions for each run are given later. The average energy of the fragments on each roll of film was computed and its constancy taken as an indication of stable gas properties.

C. Pulse Shaping Circuits

A summary of some of the common methods of pulse shaping is given in Fig. 13.

The properties indicated for the open and closed line are quickly developed from the transmission line equations. For example, consider an ideal closed matched line (see Fig. 13). The input impedance of line and resistance in parallel is:

\[ Z_{\text{in}} = \frac{Z_0(j\tan\theta)}{1 + j\tan\theta} = Z_0 \sin \theta (\sin \theta + j\cos \theta) \]

\[ = Z_0 \sin \theta \sqrt{(\frac{1}{2} - \theta)} \]

Defining the reference voltage for the gain as \( IZ_0 \) we get:

\[ K = \text{gain} = \frac{I(Z_0 \sin \theta \sqrt{(\frac{1}{2} - \theta})}{IZ_0} = \sin \theta \sqrt{(\frac{1}{2} - \theta)} \]
Fig. 13. Properties of Delay Lines, Integrators and Differentiators.
The following is intended as a summary of the properties of

The definitions of differentiation and integration are

In the table, we have made a distinction between those

In the table we have made a distinction between those

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<th>CASE</th>
<th>USE</th>
<th>LIMITS OF USE</th>
<th>STEADY STATE GAIN</th>
<th>DRIVING SOURCE</th>
<th>TRANIENT RESPONSE</th>
<th>REMARKS</th>
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<tr>
<td>OPEN LINE</td>
<td>Time clipper with differentiators if 0 is very small.</td>
<td>( V_V1 )</td>
<td>( V_V1 )</td>
<td>Voltage Source</td>
<td>( Y_V1(1) )</td>
<td>STEADY STATE GAIN FOR RC CURVE</td>
</tr>
<tr>
<td>CLOSED LINE</td>
<td>Time clipper</td>
<td>( V_V1 )</td>
<td>( V_V1 )</td>
<td>Current Source</td>
<td>( Y_V1(1) )</td>
<td>STEADY STATE GAIN FOR RC CURVE</td>
</tr>
<tr>
<td>DIFFERENTIATION</td>
<td>Good if ( G_{RC} = C_1 \cdot Q )</td>
<td>( 1 )</td>
<td>( 1 )</td>
<td>Voltage Source</td>
<td>( Y_V1(1) )</td>
<td>GOOD FOR DIFFERENTIATING LINES.</td>
</tr>
<tr>
<td>INTEGRATION</td>
<td>Good if ( WRC \approx 0 )</td>
<td>( 1 )</td>
<td>( 1 )</td>
<td>Voltage Source</td>
<td>( Y_V1(1) )</td>
<td>GOOD FOR INTEGRATING LIINES.</td>
</tr>
</tbody>
</table>

FIG. 13
The transient response is the difference between incident and reflected wave.

\[ V_2(t) = \frac{Z_0}{2} (i(t) - i(t-T)) \]

In terms of transmission line constants \( T \) equals \( \frac{2\theta}{\omega} \). In equation 8 let \( i(t) = I_0 e^{j\omega t} \).

\[ V_2(t) = \frac{Z_0}{2} I_0 e^{j\omega t}(1 - e^{j\omega T}) \]

\[ = I_0 Z_0 e^{j\omega t}(\sin \theta)\sqrt{\frac{\pi}{2} - \theta} \]

If we divide equation 9 by \( I_0 Z_0 e^{j\omega t} \) the result is identical with equation 6. The analysis of the open line case is similar. In fact, as the difference equation is identical in form, we expect the same result.

The differentiating circuit is easily analyzed by considering it as a four terminal network and adopting Guillemin's notation. We get:

(10) \[ v_1 = \alpha v_2 - \beta i_2 \]

\[ i_2 = -v_2 Y_L \]

(11) \[ v_1 = v_2 (\alpha + \beta Y_L) \]

(12) \[ K = \frac{v_2}{v_1} = \frac{1}{\alpha + \beta Y_L} \text{ transfer gain} \]

By considering open and short circuited conditions we get:

(13) \[ Q = \frac{c_1 + c_2}{c_1} \]

\[ \beta = \frac{1}{j\omega c_1} \]
Thus:

\[
\frac{V_2}{V_1} = K = \frac{1}{c_1 + \frac{1}{\omega c_1 R}} = \frac{c_1 + c_2}{c_1} (\omega R c_1)^2 + j \omega R c_1 \\
1 + (\omega R c_1)^2 \frac{c_1 + c_2}{c_1}^2
\]

From equation 14, the transfer Laplace transform is:

\[
K(s) = \frac{1}{c_1 + \frac{1}{\omega c_1 R}} = \frac{s (c_1 + c_2)}{s + \frac{1}{R(c_1 + c_2)}
\]

Letting the driving function be a linearly rising voltage, \( V_1 = Kt \) yields:

\[
V_2(s) = V_1(s) K(s) = \frac{K c_1}{s + \frac{1}{R(c_1 + c_2)}
\]

Application of the inversion integral for the inverse transform gives:

\[
V_2(t) = K R c_1 (1 - e^{-\frac{t}{R(c_1 + c_2)}})
\]

The analysis of the integrating circuit is similar.

In these experiments, current sources with shorted line clippers are used. The integrating-differentiating test of the parallel plate ionization chamber also used a differentiating circuit. The pulse lines are shown in Figs. 14 and 15. The capacity calculation of the distributed constant lines can be adequately done by assuming concentric cylinders for the wire and foils. By foil is meant the split copper foil wrapped around the polystyrene rod and helical winding as shown in Figs. 14 and 15. The lumped-constant lines have been calculated in a standard fashion. The matching resistors were experimentally determined.
Fig. 14. Delay Line Clippers, Diagrams.
(a) The figure shows a distributed-constant delay line clipper.
(b) The figure shows a lumped-constant delay line clipper, or pulse forming network.
DISTRIBUTED CONSTANT LINE CLIPPER

FIG. 14a

LUMPED CONSTANT LINE CLIPPER

FIG. 14b

\[
C_1 = C_0 = 250 \, \mu F
\]

TOTAL \( L \sim 50 \, \mu F \)

MU 487

CABLE CONNECTOR

LAYER OF TAPE PLACED OVER OUTSIDE OF COPPER SHEET

3" OF #21 FORMVAR COVERED WIRE ON 1" BAKELITE TUBING

120 OHMS

100 OHMS

C1

C2

C9
Fig. 15. Delay Line Clippers, Photographs.
In the top part of the photograph can be seen a lumped-
constant pulse forming network. The bottom part of the
photograph shows two distributed constant delay lines.
The upper one is shown before the outer layer of foil
is added.
D. Amplifiers

The amplifiers used are shown in Figs. 16 and 17. The main amplifier is a standard Radiation Laboratory model designed by G. Essex. The pre-amplifier has been designed by Watkins analysis and has the response indicated.

Three points about the design of stable amplifiers are worth mentioning. First, a cathode follower has a sensitivity approximately equal to $1/(1 + g_m R_k)$. The sensitivity is a measure of stability of the gain to component or voltage change as defined by Bode. This is unfortunately low for most wideband design. Thus cathode follower output is avoided in the preamplifier. The long-time stability of a cathode follower can be improved by the use of a large positive grid bias voltage. This is important in circuits where from a practical standpoint one is forced to use a cathode follower. Second, the long-time stability of screen grid tubes can be improved by using a very large screen bleeder resistance. As a consequence, the bleeder must be run to a high voltage. In effect, this is a negative feedback circuit involving the screen-plate transconductance and the screen resistance. Third, long-time triode stability can be improved by use of a large plate resistance to direct current; this requires a large plate supply voltage. Fig. 18 illustrates these three points. These circuits stabilize the direct plate current through the tube and thus the transconductance. It should be noted that changes in contact potential, cathode temperature, cathode surface and applied voltage are gradual. Drift due to these variables is reduced by the above circuits. The alternating current feedback is left mainly to provide linearity of gain and short-time stability. These suggestions are not in common usage, but will probably be included in future designs of this laboratory. The practice of many laboratories of supplying less than 150 volts to a preamplifier is not good engineering.
Fig. 16. Preamplifier.
The wiring diagram of the preamplifiers for the double ionization chamber is shown.
FIG. 16

PREAMPLIFIER

MU 488

14919-1
Fig. 17. Amplifier. The wiring diagram of the amplifiers for the double ionization chamber is shown. This is a standard Radiation Laboratory model.
Fig. 18. Current Stabilization of Vacuum Tubes. The following illustrates methods of stabilizing the plate current through a vacuum tube.
GENERAL CASE

CATHODE FOLLOWER

$E_6$: PLATE SUPPLY VOLTAGE

$R_L$: SCREEN RESISTOR

$R_C$: CATHODE RESISTOR

$T_{bb}$: TRIPLE AMPLIFIER

$Y_{pp}$: PENTODE AMPLIFIER

$R_{L1}$: LARGE SCREEN RESISTANCE

$R_{L2}$: LARGE PLATE RESISTOR

NOTE:

In practice, if a regulated power supply is used ($\delta_{bb} \neq 0$), tube characteristic changes can be written as an effective ($\delta_{pp}$).

:\input{fig18}

\textbf{FIG. 18}
The fission rate measurements were made with very short clipping time, 0.1-0.2 microseconds, and eight megacycle bandwidth. The energy measurements were taken with a bandwidth of two megacycles and 0.5-0.7 microsecond clipping time.

E. Discriminator

Fig. 19 shows the amplitude discriminator. An amplitude discriminator is defined as a device that gives a fixed output pulse whenever it receives an input pulse greater than a predetermined amplitude. This blocking oscillator design is satisfactory when triangular pulses one tenth of a microsecond wide are its input. The standard diode discriminator is unsatisfactory with such pulses; the energy in the peak of the pulse is just too small.

A diode discriminator is limited by the transfer characteristics of both the diode and some later stage. The circuit shown is limited by the sharpness of cut off of the 6AG5 and the gain and bandpass around the blocking oscillator loop. The blocking oscillator requires a pulse greater than a certain size on its grid to trip. In practice this means that the energy represented by a given bias voltage is proportional to that voltage except for an additive constant. The synchronization pulses provided by the discriminator are approximately 0.5 microsecond wide and 60 volts in magnitude. The negative gate is to gate a pulse extender. The pulse extender was not used in these experiments.

The "parallel" switch of the discriminator arranges the circuit so that a pulse sufficient to trip a channel will give an output from both circuits. Thus, an event representing an energy greater than the bias setting in its channel will trip all photographic and recording equipment.
Fig. 19. Discriminator.
The wiring diagram of the two channel discriminator is shown. The circuit will respond to pulses of a triangular shape 0.1 microsecond wide at the base.
F. Pulse Extender

The unused pulse extender schematic is shown in Fig. 20. The purpose of the pulse extender is to receive a pulse of 0.1 microsecond duration, to preserve its amplitude and to extend its length to several seconds. It is intended that this extended pulse be used to drive an Esterline Angus graphic recorder. It was thought at first that a chart might provide a more convenient method of taking data than film. The matter of convenience is questionable and any extender is obviously subject to photographic checks. Four factors were mainly responsible for its abandonment: first, the problem of cascading voltage drops across the charging diodes was never solved; second, the recorders proved to be much less accurate than the manufacturer claimed; third, the extender and recorder will never be more accurate than photographs; and fourth, the stability of the cathode followers is poor. The extender shown operates satisfactorily when crystal diodes are used instead of 6AL5 vacuum tubes. Due to current limitations it requires a longer input pulse when operated in this fashion.

G. Shielding and Voltage Stabilization

Initially it was felt that one of the major problems would be the elimination of spurious counts from the equipment which because of the short-time resolution time must be broadband. Discussion with members of the instrument group at the Radiation Laboratory indicated that the linear amplifiers gave a few spurious counts per hour when sitting on a bench with input shorted. The block diagram, Fig. 4, indicates that LC filters are used on the 110 volt alternating current supply and plate supply of critical units. In addition, these units are in a modified Bud cabinet with all of its ports and openings covered with layers of crossed copper mesh. Fig. 21 shows the final arrangement.
Fig. 20. Pulse Extender.
The wiring diagram of the unused-pulse extender is shown.
NOTE:
CRYSTALS MAY BE USED INSTEAD OF CHARGING DIODES

MU 491

PULSE EXTENDER

Fig 20.
Fig. 21. General Equipment Photograph.
The rack on the right contains the ionization chamber and amplifiers. The left hand rack contains the power supplies, discriminator and scalers. The camera drive equipment mounted on the light tube of one of the synchrosopes can be seen in the left foreground.
As indicated in the block diagram, all equipment is run from saturable reactor voltage regulators. In addition, the B plus supply voltage is always obtained from voltage regulated power supplies. The beam voltage for the cathode ray tubes is also obtained from a voltage regulated supply.

It is interesting to note that the front covers, one of which has been removed in Fig. 19, must be in place on the Bud cabinet to prevent spurious counts. This implies that the radio frequency pickup of the equipment is serious.

The equipment has been run for many days without spurious counts.

H. Camera Equipment

The cameras used for photographing the synchroscopes are Leica cameras with f-2 lenses; this choice was dictated by their availability. The shutters are left open at all times. A Corning number 5030 blue filter is used to eliminate the cathode glow. Eastman super XX film is used and as indicated in the Dumont Handbook one can photograph 1 microsecond per inch sweeps with 5000 volts beam accelerating potential. This was done for the study of pulse shapes. For the fission pulses a slower sweep and 4000 volts accelerating potential are used.

The camera film is advanced by an electric drive after each event. It can be seen from Figs. 22 and 23 that the motor is turning over at all times. When a synchronizing pulse is received a solenoid is excited, meshing the gears. The resulting advance is stopped when a screw placed in any of the twelve equally spaced holes on the camera drive wheel strikes a microswitch. This arrangement permits advancing the film only a small fraction of a frame after each event. Most of the horizontal sweep is masked out on the face of the cathode ray tube. The camera drive is usually run with eleven photographs to a normal 35 mm. frame.
Fig. 22. Camera Drive Circuit.
The wiring diagram of the camera drive equipment is shown. The control chassis is mounted on one of the synchroscope table shelves and connected by a cable to the drive unit mounted on the light tube (Figs. 21 and 23).
Fig. 23. Camera Drive Photograph. The driving wheel with the twelve screw holes can be seen in the center of the photograph. The microswitch is in the upper right hand corner. The tripping solenoid is in the upper left hand corner. The shaft through the driving wheel connects to the camera. If the camera jams, the direction of rotation is such that the motor gear (rotating in the picture) will disengage the idler gear and just grind teeth with it.
A Flexopulse timer lights a small bulb in front of the camera at adjustable intervals. The light is on for thirty seconds. This permits alignment checks on the two channels. Fig. 30 shows some typical photographs.

I. Film Construction

The films were constructed by spreading a formvar E-ethylene dichloride solution on water and letting it dry. The water is kept at approximately zero degrees centigrade for best results. A drop of solution from an eyedropper spreads very nicely. By lowering a thin two-inch metal disk with a one-inch hole in it onto the film it can be picked up off the surface of the water. After the moisture has dried the process is repeated giving a double film. The weight of sample double films was found to be 10-15 micrograms per square centimeter.

The film can also be picked up by approaching it from below. The films placed on the Lectromesh were picked up by this method. Lectromesh is a commercial screen or mesh suitable for use as a collimator.

J. Evaporator

The samples for the double ionization chamber are made by evaporating active material onto a thin formvar E film. The evaporation is from a hot filament in a vacuum. The filament is one mil tungsten strip with a dish-like dent in it. Fig. 24 shows the equipment. If desired, the film is made conducting by later evaporating a thin coating of gold or copper onto the film. The weight of film plus gold coating was found to be 20-40 micrograms per square centimeter.

In the case of curium the material evaporated was a chloride solution. As indicated in Fig. 24, the evaporator is built into a glove box so that large amounts of activity can be handled.
Fig. 24. Evaporator Glove Box.
The glove box proper is a standard item of the Health Chemistry group of the Radiation Laboratory. The vacuum pump and control panel can be seen below the box proper. The top of the metal bell jar can be seen inside the box just above the control panel. The oil diffusion pump is behind the electrical control panel. This modified glove box is used for evaporation of large amounts of very active material.
K. Calibration

The calibration of the equipment assumes that the ionization per unit energy of fission fragments equals that of alpha-particles. The chamber performance was checked with an uncollimated Am$^{241}$ plus Cm$^{242}$ sample. Fig. 25 shows the results of such a check. The photograph shows many disintegrations. This may also be used as a calibration for the equipment. The test was done at 20 pounds per square inch gas pressure to insure that the alpha-particles were stopped in the cathode-grid region. The chamber was insensitive to pressure and voltage changes in this region. The gain was reduced by a factor of sixteen for fission runs. The pressure was reduced to slightly above atmospheric. A more reliable method of calibration is the energy distribution of the fragments from slow neutron fission. Before the voltage plateau for the chamber has been reached, it has been observed that voltage changes shift the effective gain of the equipment and do not change the shape of the energy distribution curve. Calibration is discussed further in a later section.

The attenuators were calibrated with a General Radio type 369A pulse generator. This was connected to the cathode of the ionization chamber with the grids grounded. The shielding action of the grids is not perfect and some of the signal appears on the plates. Each step of the attenuator reduces the signal by a factor of two. This change was measured photographically and by observing the maximum bias voltage at which counts were registered.

The linearity of the amplifiers was checked by the same procedure. The voltage output for two attenuator settings was measured for larger and larger input signals.
Fig. 25. Chamber Resolution Check.
(a) Bias curve for one side of the double chamber with an Am$^{241}$ and Cm$^{242}$ alpha sample. The Am$^{241}$ and Cm$^{242}$ alpha-particles are clearly resolved.
(b) The photograph is of the pulses for the conditions given in part A. The time exposer shows many events.
FIG. 25 a

THIN Am$^{241}$ + Cm$^{242}$
SAMPLE ON PLATINUM PLATE

Am$^{241}$ PLATEAU
5.48 MEV

Cm$^{242}$ PLATEAU
6.08 MEV

Cm$^{242}$
6.08 MEV

Am$^{241}$
5.48 MEV

FIG. 25 b

COUNTS / MIN.

BIAS VOLTS
Daily checks of the amplifier gain were made with the pulse generator of Fig. 26. Again, the pulser was connected to the cathode with the grids grounded. The results were measured both photographically and by the bias cut off point. The amplitude of the signal from the pulse generator is a function only of battery voltage, relay contact resistance and passive element characteristics. All of these possible variables are very constant.

III. EXPERIMENTAL CONSIDERATIONS

The equipment used is described in the previous section. The present section describes some general considerations of data analysis. The description includes details of the samples prepared, the errors to be expected and methods of data analysis.

A. Samples

The samples prepared for this experiment were on thin plastic films. Fig. 27 shows the important details and properties of the samples. In all cases, except one $^{235}$U sample, the active material was deposited by vacuum evaporation.

B. Films

The advantages of a conducting film can be understood by considering the two limited cases of film resistance: specifically, a perfect conductor and a perfect insulator. The case of a perfect conductor is well understood. For a perfect insulator consider free space. The fact that free space has a dielectric constant and permeability different from a film is not too important. The current induced in a chamber by a moving charge $q$ is given in Fig. 5 as:

$$i = \frac{d}{dt} \left( Q v \cdot \overrightarrow{E}_a \right) = Q \frac{d}{dt} \left( \frac{d\phi_a}{ds} \right) = Q \frac{d\phi_a}{dt}$$
Fig. 26. Pulse Generator.
39K

-16½ VOLTS FROM DRY BATTERY

+ 5

-3 RELAY

110 VOLTS A.C. 22 VOLTS D.C. FROM DRY BATTERY

PULSE OUT

C1 = ⋯ = C7 = .001 µf

NOTES

RELAY: WESTERN ELECTRIC TYPE D-168479 RELAY

PULSE NETWORK: SEE FIGURES 14 AND 15 FOR TYPE ON CONSTRUCTION

MU 493

FIG. 26
Fig. 27. Samples.
The table shows the samples prepared for this experiment. The sample properties and constructional details are indicated. In all cases, the upper side of the sample is the channel II side.
(a) U235-I
(b) Cm242-I
(c) Cm242-II
(d) Cm242-III
(e) U235-II
Active material: \( \text{U}^{235} \)

Run channel II only

With and without collimation

4820 cc/m

Purifier: oxygen absorber and drier

Neutron source: PoBe

All field strengths

Preparation: unknown

MU 494

FIG. 27a
Active material: Cm$^{242}$

No collimation

$8.4 \times 10^6$ ac/m

Purifier: oxygen absorber

Pres: 4 lbs/in$^2$ Gauge

Sample-grid field strength = 1500 volts/in

Grid-collector field strength = 3000 volts/in

Preparation: Vacuum evaporation

MU 495

FIG. 27 b
Active material: Cm$^{242}$

Collimation on one side
5.8 x $10^6$ ac/m non-collimated side

Purifier: oxygen absorber
Pressure: 4 lbs/in$^2$ Gauge

Sample-grid field strength = 1500 volts/in$^2$

Grid-collector field strength = 3000 volts/in$^2$

Preparation: vacuum evaporation

MU 496

FIG. 27c
Active material: Cm$^{242}$

Collimation one side

$9.3 \times 10^6$ ac/m non-collimated side

Purifier: oxygen absorber, drier and circulating pump

Pressure: 4 lbs/in$^2$ Gauge

Sample-grid field strength = 1500 volts/in$^2$

Grid-collector field strength = 3000 volts/in$^2$

Lectromesh: a commercial square grid about 30% transparent. The collimation removes all particles below 30°.

Preparation: vacuum evaporation

FIG. 27 d
Two samples prepared and run back to back in double chamber

Active material: 96% $^{235}\text{U}$

No collimation

9220 and 4820 ac/m

230 and 120 micrograms

Purifier: oxygen absorber, drier and circulating pump

Pressure: 4 lbs/in$^2$ Gauge

Sample-grid field strength = 1500 volts/in

Grid-collector field strength = 3000 volts/in

Preparation: vacuum evaporation

MU 498

FIG. 27e
Fig. 28 shows approximate plots of the field in the chamber, $\vec{E}$, and the field $E_a$ in equation 18. The electrons very closely follow the lines of $\vec{E}$. Integrating equation 18 gives equation 19.

\[
(19) \int \frac{d\phi_a}{dt} dt = Q \int d\phi_a = Q \phi_a
\]

Consider a parallel plate chamber. It is quite clear that as $\frac{d\phi_a}{dt}$ is a function of position a conducting film is required for energy measurements. The value of $\phi_a$ is also different. In the case of a grid chamber the grid shields the plate from the cathode-grid region and a conducting film is not needed. Both $\phi_a$ and $\frac{d\phi_a}{dt}$ are zero in the cathode-grid region. However, the value of $\vec{E}$ must not drop to a point where recombination is important. For this reason a conducting film may still be required. The currents drawn are very small and the film can have a high resistance. Thin conducting films are easy to make and were used.

The effect of finite film thickness is easily derived from Fig. 29. The notation is included on the figure. Assume the energy loss per unit path length is a constant.

\[
(20) \frac{dT}{dr} = K
\]

This is not true for fission fragments but for short path lengths the assumption is valid. The solid angle between $\theta$ and $\theta + d\theta$ is:

\[
(21) d\phi = \text{solid angle} = 2\pi \sin \theta \, d\theta
\]

If there are $N_0$ mono-energetic particles per unit time given off on one side of the film, the number of particles between $\theta$ and $\theta + d\theta$ is:

\[
(22) dn = -N_0 \sin \theta \, d\theta
\]

The energy loss is equal to:

\[
(23) T_0 - T = \frac{kU}{\cos \theta}
\]
Fig. 28. Double Ionization Chamber Theory. The figure shows free-hand sketches of the fields that are important in an ionization chamber.
PARALLEL PLATE CHAMBER FIELD PLOTS

FIG. 28a

FIG. 28b

\[ I = q \frac{V}{E_0} \]

*PATH OF ELECTRONS DETERMINED BY $E$, FIG. 28a*

$E_0$, SHOWN IN FIG. 28b.

FIELD PLOTS ARE APPROXIMATE FREEHAND SKETCHS

MU 499
Fig. 29. Film Absorption Theory. The figure illustrates the geometry and notation used in calculating the effect of a thin film.
\[ \frac{dT}{dr} = K = \text{ENERGY LOSS PER UNIT PATH IN FILM} = \text{CONSTANT} \]

\( \sigma = \text{THICKNESS OF FILM} \).

\( N_0 = \text{MONOENERGETIC PARTICLES PER UNIT TIME EMITTED FROM O IN UPPER HALF PLANE} \).

\( \phi = \text{SOLID ANGLE IN CONE OF ANGLE } \theta \text{ AROUND OV} \).

\( T = \text{KINETIC ENERGY OF PARTICLE} \).

\( T_0 = \text{INITIAL VALUE OF } T \).

MU 500

FIG. 29
This assumes the particles are not appreciably deviated from a straight path.

Solving for \( d\theta \) in equation 23 and substituting in equation 22 give:

\[
(24) \ dN = \frac{N_0 K \sigma^-}{(T_0 - T)^2} \ dT
\]

From which:

\[
(25) \ \frac{1}{N_0} \frac{dN}{dT} = \frac{K \sigma^-}{(T_0 - T)^2}
\]

The number of particles per unit time escaping with energies between \( T_1 \) and \( T_2 \) is:

\[
(26) \ \int_{T_1}^{T_2} dN = \frac{N_0 K \sigma^-}{(T_0 - T)} \bigg|^{T_2}_{T_1}
\]

If the limits of \( T_1 \) equals zero and \( T_2 \) equals \( T_0 \) minus \( K \) are put in equation 26, the fraction of particles getting out of the film is found to be \( (1 - \frac{K \sigma^-}{T_0}) \).

This is the count that would be observed with a four pi counter using a film.

The fraction of escaping particles with energy less than \( (T_0 - n \sigma^- K) \) is:

\[
(27) \ \int \frac{N_0 K \sigma^-}{T_0 - T} \ \bigg|^{T_0 - n \sigma^- K}_{T_0 - K \sigma^-} = \frac{N_0 (1 - \frac{K \sigma^-}{T_0})}{n \sigma^- T_0} \sim \frac{1}{n}
\]

This is valid if \( \frac{K \sigma^-}{T_0} << \frac{1}{n} \)

One-fifth of the particles have an energy loss greater than five film thicknesses. Collimation is desirable.

C. Accuracy

The accuracy that can be expected from the photographic method is not too good. The photographic film can probably be read to plus or minus one division. The deflections go up to forty divisions. Fig. 30 is a typical
Fig. 30. Typical Data Photographs.
FIG. 30

CHANNEL I

GAIN CALIBRATION MARKS - CONTINUOUS FILM ADVANCE

FISSION PULSES

LIGHT IN FRONT OF CAMERA

CHANNEL II

GAIN CALIBRATION MARKS - CONTINUOUS FILM ADVANCE

FISSION PULSES

LIGHT IN FRONT OF CAMERA
section of film. The film is read by projecting it onto the wall of a darkroom. The projector is clamped down to maintain a constant spacing.

There is a chance that an alpha-particle will be emitted by one nucleus coincidental with the fissioning of another nucleus. Coincidental events can be taken as events occurring within the resolving time of the equipment. This probability is evaluated from Poisson's law as follows:

\[
(28) \quad P(n-1) = \frac{(\gamma N_0)^{n-1}}{(n-1)!} - \frac{\gamma}{n-1} \cdot \frac{(1)^{n-1}}{(n-1)!}
\]

where \((\gamma N_0) \approx (10^{-6} \times 10^5) = 10^{-1}\)

\(P(n-1)\) is the probability of \((n-1)\) alpha pulses occurring in time \(\gamma\) after a fission pulse. \(N_0\) is the normal counting rate of alpha-particles. Conservative values of \(\gamma\) and \(N_0\) have been used. One fission fragment out of ten will have an alpha-particle superimposed on it. One fission fragment out of two hundred will have two alphas superimposed on it. The above remarks assume rectangular pulses and that partial coincidences are important. The results are not exact and are to be taken as an estimate.

The alpha pile-ups that trip the discriminator are described in the section on fission bias curves. Such an event is very unlikely to occur in both sides of the chamber at the same time.

The frequent checks made on the electronic equipment eliminate it as a major source of error.

A major source of error is the assumption that a fission fragment's ionization per million electron volts is linear with energy and equal to that of an alpha-particle. This is an assumption made by all workers with ionization chambers. Henderson's calorimeter measurements indicate that as far as total energy is concerned this is valid to five or ten percent. However,
the major assumptions are known to be incorrect. The exact size of the error is not known. Attempts to attribute the disagreement between the mass yield curve and energy curve of slow neutron fission to this error have not been completely satisfactory. Hanna and Burton in their recent paper\textsuperscript{17} have discussed this in detail. To really examine the phenomenon the high flux of thermal neutrons available in a pile is needed. The counting rate of spontaneous fission is too low. Besides, the mass fission yield curve, Fig. 1, is only known for neutron fission.

The primary energy calibration of this experiment is slow neutron fission. The assumption is made that the results of previous workers are correct. This puts the spontaneous and slow neutron results on the same basis for comparison purposes.

The slow neutron cross section of Cm\textsuperscript{242} is very low and fission from this source is not important. Unless fissions other than binary occur in a much larger proportion than in slow neutron fission\textsuperscript{55} this is not a significant factor either.

D. Data Presentation

The data taken is assembled on a three dimensional plot. Fig. 31a is an example of the plot used. Each square represents a fixed energy division between fission fragments. A check is placed in the corresponding square for each event. The chart can later be drawn as a three dimensional continuous plot. The single sided energy distribution can be obtained by summing each column or row.

Certain facts about Fig. 31a are of interest. These facts are plotted in Fig. 31b. The constant total energy lines are:

\[ E_1 + E_2 = E_T = E_2 \]
Fig. 31. Data Presentation.
Part a shows the three dimensional plot used to assemble data.
Part b shows some facts of interest about Fig. 31a.
FIG. 31a

PULSE HEIGHT CHANNEL I (PROPORTIONAL TO ENERGY)

FIG. 31b

E\textsubscript{2} \cdot \frac{m\textsubscript{2}}{m\textsubscript{1}} E\textsubscript{1}

LOCUS OF CONSTANT MASS RATIO AND CONSTANT MASS

LINE OF SYMMETRY REQUIRED BY CONSERVATION OF MOMENTUM.

E\textsubscript{2} \cdot \frac{E\textsubscript{2}}{(m1 + m\textsubscript{2}) - 1} m\textsubscript{1}

LOCUS CONSTANT MASS M\textsubscript{1} & CONSTANT MASS RATIO

E\textsubscript{2} \cdot E\textsubscript{T} - E\textsubscript{1} LOCUS OF CONSTANT TOTAL ENERGY E\textsubscript{T}

FIG. 31b
Equating the square of momentum for the two fragments:

\[ 2M_1 \left( \frac{M_1 v_1^2}{2} \right) = 2M_1 E_1 = 2M_2 E_2 = 2M_2 \left( \frac{M_2 v_2^2}{2} \right) \]

or,

\[ \frac{E_1}{E_2} = \frac{M_2}{M_1} \]

In all calculations involving momentum the momentum of prompt neutrons, alpha-particles, and gamma-ray is assumed small and not calculated. The locus of constant mass ratio points is:

\[ E_1 = \frac{M_2}{M_1} E_2 \]

Equation 32 may be written as:

\[ \frac{E_1 + E_2}{E_2} = \frac{M_1 + M_2}{M_1} \]

The sum of the masses is approximately equal to the mass of the initial atom, a constant. Thus the locus of constant mass, \( M_1 \), points is given by:

\[ E_1 = \left( \frac{M_1 + M_2}{M_1} - 1 \right) E_2 \]

The three dimensional plot can be written in mathematical form as:

\[ f(E_1 E_2 \mathbf{F}) = 0 \]

The single fragment energy curve is then obtained by plotting the sums of the columns.

\[ f(\left\{ \begin{array}{c} E_2 = \infty \\ E_2 = 0 \end{array} \right\}) = f(E_{11} P_{11}) = 0 \]

The discontinuous plot can be represented by summation equations.
The depth of the valley of the one dimensional plot, Fig. 2, is often incorrectly taken as an indication of the symmetry of fission. A symmetrical fission will lie approximately on the line $E_1 = E_2$ in Fig. 3lb. This follows from the conservation of momentum, or equation 32. It is easy to imagine a three dimensional plot with no symmetrical fission whose single fragment energy curve is single-peaked. Most instrumentation errors will spread out the three dimensional probability peaks. The spread will result in more overlap of the peaks when viewed from one of the co-ordinate directions. Consequently, the valley of the single fragment energy curve will be raised. In all probability it will not place counts on the symmetrical fission locus of $E_1$ equals $E_2$. The valley of the single fragment energy curve is not a good indication of symmetrical fission and its nature is greatly changed by most instrumentation errors. A vertical section through the two peaks would provide a two dimensional curve whose valley is an indication of the degree of symmetrical fission.

E. Data Correction Methods

The two dimensional energy curve obtained from summing in one coordinate direction must agree with that obtained by summing in the other direction. This is just another way of saying that the information obtained on one side of the film must agree with the results of the other side. This demands that the three dimensional energy plot be symmetrical around a forty-five degree line through the origin. Due to energy absorption in the foil or collimator this condition may not be satisfied. Assume the active material is on the channel two side of the film (Fig. 4). Postulate that particles going into the channel one side lose energy. Assume further that the information obtained from channel two is correct. Impose the condition of symmetry. Can the information from channel one be corrected to what it should be?
The particles entering channel one have passed through a foil and possibly a collimator. This energy loss causes the particles to be displaced towards the origin along the $E_1$ axis of Fig. 31a. It seems reasonable to assume that during this displacement the order of the particles remains the same. In effect the plot is being compressed in the $E_1$ direction. The plot in the $E_2$ direction is presumably correct. A good deal of thought has been put into the problem of correcting the three dimensional plot under these conditions. It is felt that these assumptions are necessary and sufficient for making a correction. However, no rigorous mathematical existence proof or method is evident. The following intuitive method is presented without formal mathematical proof of its validity. The statements refer not to the individual particles but to the most probable particle, i.e., to energy positions on the three dimensional plot.

Assume that the channel two information is correct. Primed values indicate uncorrected values in channel one.

\[(37) \quad P_2 = f_2(E_{22}) = P(E)\]

From symmetry:

\[(38) \quad P_1 = f_1(E_{11}) = f_2(E_{22}) = P(E)\]

A correction function, $g(E(E_{11} - E))$, is defined so that:

\[(39) \quad P'(E_{1}) = \int_{E=0}^{E=\infty} (P(E))g((E)(E-E_{1})) \, dE\]

Each area $P(E) \, dE$ is spread out by the factor $g$. If a $g$ satisfying equation 39 can be found it can be used to correct the three dimensional plot. The solution involves integral equations the terms of which are not known in analytic form. The summation equation corresponding to equation 39 is given in equation 40. The $E$ axis is divided into units $\delta$ as indicated in Fig. 32.
Fig. 32. Data Correction.
Part a indicates the correct data from channel II and the incorrect data in channel I.

Part b indicates how a section of the channel II histogram is spread out in channel I as a result of energy loss in film or collimator.
$P'(E)$

$P(n_x)$

$P(E)$

$N_y$ $E$

$P'(E)$

$P(n_x)$

$P(E)$

$N_y$ $E$

**CHANNEL ONE PLOT**

**CHANNEL TWO PLOT**

**FIG. 32a**

$P(n)$

$P(E)$

$N_x$ $E$

$P(n)$

$P(E)$

$N_x$ $E$

**CHANNEL ONE PLOT**

**CHANNEL TWO PLOT**

$P(n)$ in channel two is spread out as indicated.

**MU 502**

**FIG. 32b**
The integral can be removed by a coordinate change; the particles can only lose energy and \( P(n) \) equals zero for \( n \) greater than some value, say \( n_y \). Equation \( 40 \) becomes:

\[
(41) \quad P^y(n_x) = \sum_{n=n_x}^{n_y} P(n) \, g((n)(n-n_x))
\]

Assume equation \( 41 \) can be solved by approximation for \( g \). Let \( n = n_y \).

\[
(42) \quad P^y(n_x) = P(n_y) \, g((n_y)(0)) = P^z(n_z)
\]

For all values of \( n_x \) greater than \( n_z \), \( P^y \) equals zero. Solving equation \( 42 \) for \( P(n_y) \) gives:

\[
(43) \quad P(n_y) = \frac{P^z(n_z)}{g((n_y)(0))}
\]

The expression for \( P^y(n_{z-1}) \) is:

\[
(44) \quad P^y(n_{z-1}) = P(n_{y-1}) \, g((n_{y-1})(0)) + P(n_y) \, g((n_y)(1))
\]

\[
(45) \quad P(n_{y-1}) = \frac{1}{g((n_{y-1})(0))} \left\{ P^y(n_{z-1}) - P(n_y) \, g((n_y)(1)) \right\}
\]

The process can be repeated many times. The general result is:

\[
(46) \quad P(n_{y-m}) = \frac{1}{g((n_{y-m})(0))} \left\{ P^y(n_{z-m}) - \sum_{n=n_y-l-m}^{n_z} P(n) \, g((n)(n-(n_y-l-m))) \right\}
\]

Equation \( 46 \) corrects the single energy two dimensional plot. The three dimensional plot can be corrected by applying the same procedure and the same function of \( g \) to each row of constant \( E_2 \) in Fig. 31a. The degrading process, calculating \( P^y \) from \( P \), involves only values of \( P \). The correction process, calculating \( P \) from \( P^y \), involves both \( P^y \) and previously calculated values of \( P \). This introduces a cumulative error and makes this calculation
less accurate. Professor Panofsky has pointed out the possibility of using the Faltung theorem\(^{48}\) of the LaPlace or Fourier transforms as a means of correcting the curve. In this particular case, the work involved would probably be greater than that presented here. If we use the LaPlace transform, we get for equation 39:

\[
(47) \mathcal{L}P'(E_x) = \mathcal{L}\left(\int_0^{E_x} P(E) g(E-E_x) \, dE\right)
\]

\[
= (\mathcal{L}(g(E_x)))(\mathcal{L}(P(E_x)))
\]

The solution is now in terms of products.

The method presented here has another advantage. In a later section a simple correction function is used based on assumptions as to what is physically taking place. Its success indicates that the physical phenomenon is probably understood.

IV. RESULTS

A. Sample \(^{235}\mathrm{U}\) – I

This sample was run to determine what field strength is required in the chamber for satisfactory operation. The neutron geometry was poor and the flux through the sample low. Insufficient data were taken for good statistics. The sample was run only in the channel two side of the chamber.

A plateau exists when the grid-to-plate and cathode-to-grid voltages exceed 1200 volts. These are equivalent to field strengths of 2400 and 1200 volts per inch, respectively.
B. Sample Cm$^{242}$-I

The properties of the sample are given in Fig. 27. The three dimensional plot of fragment oscillograph deflection and probability is given in Fig. 33. The calibration by alpha-particle energy was not too consistent. No energy calibration is indicated. The gains of the two channels were approximately identical. A later sample was calibrated with slow neutron fission but experimental changes do not permit the application of that calibration to this run.

In this run it was hoped that the information in the active channel, channel one, would be accurate. The channel corresponding to the side of the film with the active material on it is defined as the active channel. From the plot, however, it appears that both channels are very nearly identical. Several possibilities exist: first, the foil has no noticeable effect and the plot is correct; second, the chamber resolution is poor at large angles; third, the gas properties are changing and are in effect changing the gain; and fourth, the active material has worked its way into the film.

The first possibility is eliminated by the work of Segre and Weigand$^{24}$ and the Chalk River people.$^{25}$ The two dimensional plots constructed from Fig. 33 are not double peaked. Note, however, that there is no appreciable symmetrical fission. Also, the theory of the last section indicates that the film should contribute a noticeable effect.

The second possibility is not sound in light of Fig. 25 which was taken with an uncollimated sample. More important, the slow neutron fission runs resulted in a double peaked curve.

Each roll of film is originally plotted in a different color. There are not enough differences between the individual rolls for possibility three to be likely. The average deflection was also computed for each roll.
Fig. 33. Sample Cm\(^{242}\) Three Dimensional Spontaneous Fission Fragment Energy Distribution. The three dimensional plot of oscillograph deflections and probability is shown. The gains of the two channels are approximately equal. The details of sample construction and properties are given in Fig. 27.
Some differences are expected due to statistical fluctuations. For this cause of error to be real, the gas properties would have to change rapidly compared to the time required to expose one roll of film.

Possibility four is probably the truth. Close visual examination of the sample indicates that the film where the active material is has changed. This change is not immediate. After several days the shadow of the stop used over the film during activation is clearly visible. The surface of the film looks rough where the curium is. It is difficult to believe that the curium chemically attacks the film. The specific activity of Cm$^{242}$ is $8.0 \times 10^9$ disintegrations per minute per microgram. The quantity of active material is less than a hundredth of a microgram. However, the large ionization of the alpha-particles may physically damage the film. It is also possible, although not likely, that tungsten is evaporated onto the film in a large enough amount to be important. From the symmetrical nature of the plot, it appears that the curium works its way into the film. The final distribution of curium is fairly constant throughout the film.

The information of Fig. 33 is of no value except as a basis for the speculations just made. No further analysis of the data has been attempted.

C. Sample Cm$^{242}$-II

The properties of the sample are given in Fig. 27. The data from this run are plotted in Fig. 34. The gains of the two channels are approximately equal. No accurate energy calibration is available. The lack of symmetry of the plot indicates that there is a large experimental error.

Channel one, Fig. 4, was used to trip the recording equipment. As only collimated fragments enter channel one, the corresponding binary fission fragment recorded in channel two is effectively collimated. This follows from the conservation of momentum. The information from channel two is
Fig. 34. Sample Cm$^{242}$-II Three Dimensional Spontaneous Fission Fragment Energy Distribution. The three dimensional plot of oscillograph deflections and probability is shown. The gains of the two channels are approximately equal. The details of sample construction and properties are given in Fig. 27.
probably reliable. The loss of energy observed in channel one is too great to be due to the film or gold coating. Besides, such a loss in the foil would be inconsistent with Fig. 33. The only reasonable mechanism for losing the energy is for a large fraction of the electrons liberated in the fifty-mil collimator to be lost. This is a surprising conclusion but seems to be the most logical explanation of the data. The reduction of field strength in the collimator must be sufficient for recombination to become very important.

The previous section discussed methods of correcting a plot like Fig. 34. Assume that the energy lost in the collimator is a linear function of path length in the collimator. Assume further that the collimation removes all fragments more than sixty degrees from the normal and none less than sixty degrees. These assumptions are about the simplest that can be made. Equation 25 is:

\[ \frac{1}{N_0} \frac{dN}{dT} = \frac{K \sigma}{(T_0 - T)^2} = \frac{A}{(T_0 - T)^2} \]

Equation 25 is for the energy loss in a film and the postulates above correspond to this case.

In equation 39 let \( g((E)(E-E_x)) \) be defined by equation 48:

\[ g((E)(E-E_x)) = \frac{1}{(E-E_x)^2} \quad (E_x + A) \leq E \leq E_x + 2A \]

\[ = 0 \quad \begin{cases} E < E_x + A \\ E > E_x + 2A \end{cases} \]

The region in which \( g \) has a value other than zero is determined by the effective foil (collimator) thickness, \( A \), and collimation angle. The collimation angle is the angle whose cosine is \( A \) divided by \( 2A \) or sixty degrees.
Substituting equation 48 in equation 39 gives:

\[ P^0(E_x) = \int_{E=E_x+2A}^{E=E_x+A} \frac{P(E)}{(E-E_x)^2} \, dE \]

Equation 41 becomes:

\[ P^0(n_x) = C \sum_{n=n_x+2a}^{n_x+2a} \frac{P(n)}{(n-n_x)^2} \]

The film thickness converted to units of \( n \) is \( a \). The normalization factor is equal to:

\[ (50a) \quad C = \frac{1}{n=n_x+2a} \sum_{n=n_x+2a}^{n_x+2a} \frac{1}{(n-n_x)^2} \]

The equation can also be normalized by equating the areas of \( P(n) \) and \( P^0(n_x) \).

Fig. 35 gives the two dimensional, or one sided, plots of Fig. 34. Define \( n \) as the unit of pulse height shown. A reasonable value of \( "a" \) is five. Under these conditions, the information from channel two can be degraded by the operation of equation 50. In effect, channel two is assumed to be correct and used as a basis for calculating what channel one should be. Fig. 36 is the result. The small circles shown are the observed values for channel one. Considering the crude assumptions the agreement is fairly good. The major disagreement is at the low energy part of the curve.

The results of channel two can also be calculated from channel one. Equation 46 becomes in this case:

\[ (51) \quad P(n_x+a) = \frac{P^0(n_x)}{C} \sum_{n=n_x+a}^{n_x+2a} \frac{P(n)}{(n-n_x)^2} \]

Owing to cumulative errors a poorer match is to be expected.
Fig. 35. Sample Cm$^{242}$-II Two Dimensional Spontaneous Fission Fragment Energy Distribution.

Fig. 35A is the two dimensional probability plot constructed from channel I data. The fragments in this channel have passed through the collimator.

Fig. 35B is the two dimensional probability plot constructed from channel II data. These fragments are effectively collimated, but have not passed through the collimator.
SAMPLE Cm$^{242}$ – II
SPONTANEOUS FISSION OF CURIUM
CHANNEL I
COLLIMATED SIDE

FIG. 35a

SAMPLE Cm$^{242}$ – II
SPONTANEOUS FISSION OF CURIUM
CHANNEL II
UNCOLLIMATED SIDE

FIG. 35b
Fig. 36. Sample Cm$^{242}$-II Degraded Two Dimensional Spontaneous Fission Fragment Energy Distribution. The figure shown has been constructed from Fig. 35B by assuming the fragments lose energy in going through the collimator. It should agree with Fig. 35A. The small dots are Fig. 35A.
SAMPLE $^{242}$ Cm - II
CHANNEL II
UNCOLLIMATED SIDE
FIRST DEGRADING CORRECTION

DOTS ARE CHANNEL I
UNCORRECTED

FIG. 36
The result is shown in Fig. 37A. The large deviations of the curve correspond to smaller deviations in Fig. 35A. A smooth curve can be drawn through Fig. 35A and this used to obtain the values of $P^i(n_x)$. The result is Fig. 37B. The agreement between Figs. 37B and 35B is fair except at low energies. Fig. 34 indicates that the function $g$ is not very good in this region. The corrections have been made with deflections instead of energy but a calibration correction can obviously be added to the result.

The calculation of equation 51 is both less accurate and more tedious than that of equation 50. The results of Figs. 35-37 are to be taken as a first approximation. By smoothing the data from the poor channel and finding a better correction function $g$, it is believed that the three dimensional plot could be corrected. A reasonable procedure would be to correct each row of the three dimensional plot. It is more accurate to obtain data that do not need correction. The next run provided such data.

D. Sample $^{242}$Cm

The properties of the sample are given in Fig. 27. The recording equipment was tripped by channel one. It is to be noted that channel one is collimated and that channel two is effectively collimated.

The data from the run is given in Fig. 38. Fig. 38A presents the information in density plot form and Fig. 38B presents it as a numerical plot. The numerical plot is given to expedite working with the information. A contour plot could be constructed but would require smoothing of the data. The statistics are poor enough that it is felt smoothing would be deceiving. The common relation of probable error as a constant times the square root of the number of events is used with the knowledge that in this case it is not strictly correct. The energy values indicated are derived from the uranium$^{235}$ slow neutron fission discussed in the next section.
Fig. 37. Sample Cm$^{242}$-II Upgraded Two Dimensional Spontaneous Fission Fragments Energy Distribution. Fig. 37A has been constructed from Fig. 35A by correcting Fig. 35A for the fragment absorption in the collimator. The small dots are Fig. 35B. Fig. 37B is like Fig. 37A except that the data from Fig. 35A has been smoothed before calculation.
SAMPLE \( {^{242}\text{Gm}} \)
CHANNEL I
UNCOLLIMATED SIDE
FIRST CORRECTION
Dots are channel II
UNCORRECTED

FIG. 37a

SAMPLE \( {^{242}\text{Gm}} \)
CHANNEL I
UNCOLLIMATED SIDE
SECOND CORRECTION
Dots are channel II
UNCORRECTED

FIG. 37b
Fig. 38. Sample Cm$^{242}$-III Three Dimensional Spontaneous Fission Fragment Energy Distribution.

The three dimensional plot of oscilloscope deflections and probability is shown. The details of sample construction are given in Fig. 27. The values of energy have been calibrated from slow neutron fission of U$^{235}$. Symmetry conditions require that the origin be displaced as shown.

Fig. 38A presents the information as a density plot. Fig. 38B presents the information in numerical form.
SAMPLE OF $^{242}$Cm

EACH FULL MARK = 2 EVENTS
SAMPLE OF Ca$^{242}$ - III

4.0

92.7 MEV

3.0

2.0

1.0

1.0

2.0

3.0

PULSE HEIGHT

FRAGMENT T

MU 515

MU 515

F I G 3 8 b
The accuracy of the calibration will be considered at that time.

It is to be expected that the gain of the two channels will be slightly different. It is known that the amplifier gains are not identical. The almost exact agreement apparently results from the capacity unbalance in the chamber cancelling the gain variation. This remarkable fact makes the processing of data easier. The phenomenon has been observed previously on alpha-particle calibration runs.

Fig. 39 shows the two dimensional probability plots constructed from Fig. 38. There is a displacement between part A and part B that cannot be accounted for as a difference in gain. As indicated in Fig. 40, an excellent match is obtained if it is assumed that part A should be displaced 1.5 units to the right. This assumption has been made in later calculations and is shown in Fig. 38. It should be noted that 1.5 units are equal roughly to 4.3 million electron volts.

Segre\textsuperscript{56} has found the mean range of fission fragments in collodion to be roughly 2.6 milligrams per square centimeter. The formvar film used is about 10 micrograms per square centimeter and thus approximately 0.5 million electron volts of energy may be lost in the film by a particle passing vertically through the surface. Sample Cm-I indicates that the curium is probably evenly distributed throughout the film. West\textsuperscript{44} has measured the initial fragment energy loss in nitrogen as 6.5 million electron volts per millimeter of path. It follows that if all the electrons in the four mil collimator are lost they will represent approximately 0.6 million electron volts.

The alpha-activity in channel two is greater than that in channel one. However, the correction in peak position due to this source is small. Assume that the high energy peak can be expressed as a parabola.
Fig. 39. Sample Cm$^{242}_{\text{III}}$ Two Dimensional Spontaneous Fission Fragment Energy Distribution.

Fig. 39A is the probability plot constructed from channel I data. These fragments have passed through a collimator. Symmetry conditions require that the origin be displaced 1.5 units to the left.

Fig. 39B is the probability plot constructed from the data of channel II. These fragments have not passed through a collimator but are effectively collimated.
SAMPLE Cm-242
SPONTANEOUS FISSION
OF CURIUM 242
CHANNEL I
COLLIMATED SIDE

FIG. 39 a

SAMPLE Cm-242
SPONTANEOUS FISSION
OF CURIUM 242
CHANNEL II
UNCOLLIMATED SIDE

FIG. 39 b
Fig. 40. Sample Cm$^{242}$ Corrected Two Dimensional Spontaneous Fission Fragment Energy Distribution.
The fragment energy distribution for channel II. The small circles are the points for channel I after being displaced 1.5 units to the right.
SAMPLE CM $^{242}$-III
SPONTANEOUS FISSION OF CURIUM $^{242}$
CHANNEL II UNCOLIMINATED SIDE

SMALL CIRCLES ARE CHANNEL I MOVED
1.5 UNITS TO THE RIGHT

FIG. 40
\[ y = -(x-x_0)^2 + y_o \]

Let one out of \( K \) fragments have an alpha-energy \( \delta \) added to it. The resulting curve is given by:

\[ y' = \frac{K-1}{K} ((x-x_0)^2 + y_o) + \frac{1}{K} ((x-x_0 + \delta)^2 + y_o) \]

The peak of this curve is at \( x_0 + \delta/K \). If \( K \) and \( \delta \) are 10 and 5 million electron volts, respectively, the shift is 0.5 million electron volts. This estimate is probably too large and is for the total shift not the shift between sides.

The photographs for the two channels are not identical but no reading error of this size is expected. Frankly, no adequate explanation of the required displacement is obvious. Because the collimation losses are the largest unknown, channel one has been shifted to agree with channel two. It is worth noting that the presumed collimator losses with sample \( \text{Cm}^{242} \) are greater than one would expect from West's data.

The average energies shown in Fig. 39 have been calculated by computing the centroids of the fragments above and below the symmetry line. For example, in channel two the average value of all fragments below the symmetry line is taken as the average light fragment energy.

The loci of various points in the three dimensional plot have been discussed previously and are shown in Fig. 31B. A construction sheet that indicates the methods used in calculating the derived curves presented here is shown in Fig. 44.

The total energy curve, Fig. 41, has been calculated by summing the number of particles on different constant total deflection (total energy) lines. Along each constant total energy line the sum for each side of the symmetry line was taken independently. The good agreement between these
Fig. 41. Sample Cm$^{242}$-III Spontaneous Fission Fragment Total Energy Distribution. The curve has been calculated by a method indicated in Fig. 44.
SPONTANEOUS FISSION OF CURIUM$^{242}$
TOTAL ENERGY DISTRIBUTION

SAMPLE $^{242}$Cm - III

TOTAL PULSE HEIGHT

MU 508

FIG. 41
surma illustrates the symmetrical nature of the plot.

The loci of points with a total deflection of 6.4 passes very close to the two centroids of Fig. 44. Fig. 42 shows the calculated histogram along this line. The values shown are average values for the squares adjacent to the constant energy line. The abscissa is given both in terms of channel two pulse height and the mass ratio. This two dimensional plot is an indication of the lack of symmetry in fission.

The mass yield curve can be estimated from the energy plot. In Fig. 44 constant mass lines are shown. They are lines through the origin with different slopes. The area between two adjacent lines is defined as a segment. In the actual plot used the segments were distorted so that each square on the plot lay entirely within one segment. The number of events in each segment can be used to construct a crude mass yield curve. Such a mass yield curve is given in Fig. 43.

Figs. 30-43 indicate some of the information that can be obtained from the three dimensional plot. Fig. 38B has been given to permit the reader to easily construct such curves. A comparison of some of the results with those of slow neutron fission will be given in a later section.

E. Sample U\textsuperscript{235-II}

The properties of the sample are given in Fig. 27. As indicated, the sample consists of two samples on platinum run back to back. No collimation was used. The neutrons were obtained from a polonium-beryllium source. The quantity of paraffin was such that only a small fraction of the neutrons were truly thermal. Fig. 45 gives the results. The circles indicate the curium spontaneous fission data.

The camera shield of channel one was twisted on the oscilloscope during this run. The resulting pulse photographs are not perpendicular to a line
Fig. 42. Sample Cm$^{242}$-III Spontaneous Fission Fragments Mass Ratio Distribution at Constant Total Energy. The curve is given for a total energy equal to that of the average fragment. The method of constructing the curve is indicated in Fig. 44.
SAMPLE Cm$^{242}$-III
SPONTANEOUS FISSION OF CURIUM$^{242}$

FRAGMENT MASS RATIO AT CONSTANT TOTAL
ENERGY OF 64 PULSE HEIGHT UNITS

\[ \frac{E_{\pi}}{E_1} = \frac{M_1}{M_2} \]

MU 509

FIG. 42
Fig. 43. Sample Cm$^{242}$-III Spontaneous Fission Fragments Mass Yield Curve.
The mass yield curve has been calculated from the energy plot. The method of calculation is shown in Fig. 44.
SAMPLE Cm$^{242}$-III
SPONTANEOUS FISSION OF CURIUM$^{242}$

MU 510

FIG. 43
Fig. 44. Sample Cm$^{242}$-III Data Calculation Sheet. The figure illustrates the calculations made in constructing Figs. 41-43.
AVERAGE ENERGIES:

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>HE</th>
<th>LE</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>3.76</td>
<td>2.73</td>
</tr>
<tr>
<td>I</td>
<td>3.53</td>
<td>2.55</td>
</tr>
</tbody>
</table>

Sample of Cm²⁴² - III

Constant total deflections

Symmetry line

Centroid

Displaced origin

Pulse height

Fragment I 92.7 MeV

Figure 44
Fig. 45. Sample U\(^{235}\)-II Two Dimensional Slow Neutron Fission Fragment Energy Distribution. The figure shows the slow neutron fragment energy. The details of the sample are given in Fig. 27. The sample was not collimated. A correction of six parts in three hundred should be made to the abscissa of part A. The circles indicate the curve for spontaneous fission of Cm\(^{242}\).
SAMPLE U$^{235}$
SLOW NEUTRON FISSION OF
URANIUM$^{235}$

CHANNEL I

NOTE THAT THE
PULSE HEIGHT IS LOW
BY 6 PARTS IN 300
FOR U$^{235}$

CIRCLES ARE
SPONTANEOUS FISSION
OF Cm$^{242}$ DISPLACED
1.5 UNITS

FIG. 45a

SAMPLE U$^{235}$
SLOW NEUTRON FISSION
OF URANIUM$^{235}$

CHANNEL II

CIRCLES ARE
SPONTANEOUS FISSION
OF Cm$^{242}$

FIG. 45b
through the sweep starting points. The only reasonable method of reading
the film is to read the vertical deflection from this line. A correction
of six parts in three hundred should be made to the vertical deflection
and this has been done in locating the high energy peak.

As the sample was not collimated the high energy peak is the best
calibration point. An estimate of the position shift of the peak can be
made by assuming it is shaped like a parabola. An incremental layer of
the active material has a layer of active material above it. This is
identical with the film absorption theory of section IIIB. Equation 25
of that theory is:

\[
\frac{1}{N_0} \frac{dN}{dT} = \frac{K \sigma}{(T_0 - T)^2} y(T)
\]

Integration over all layers gives:

\[
y'(T_1) = \frac{1}{2K} \left( \frac{K \sigma}{T_0 - T_1} \right)^2 \quad T_1 < T_0 - K \sigma
\]

\[
= \frac{1}{2K} \left( \frac{T_0 - T_1}{T_0 - T_2} \right)^2 \quad T_0 < T_1 < T_0 - K \sigma
\]

The sample used is probably 30 micrograms per square centimeter. From
either West, Segre, or Boggild the initial energy loss in uranium
is estimated to be less than 20 million electron volts per milligram per
square centimeter. If \( K \sigma \) is equal to \((0.03)(20)\) or 0.6 million electron
volts the peak shift is roughly 0.7 million electron volts. This value was
obtained by a graphical correction of the parabola by the method of section
IIIE. The self-absorption correction is thus small.

The agreement between channels is good. It is postulated for the
purpose of calibration that the high energy peak in both channels is at
3.3 units of deflection. The results of Burton and Hanna are taken for
primary calibration. The most probable high energy fragment of their curve is at 92.7 million electron volts. This is used in preference to the average value to put both their results and those of sample U$^{235}$-II on the same basis. It should be pointed out that their result is about 1.6 million electron volts low due to the source and collimator errors. They did not make this correction when comparing their results with Deutsh and others. For consistency, it is not made here.

V. DISCUSSION

The double fragment energy distribution data of this report can be compared to the previous work with slow neutron fission. Burton and Hanna have done the most recent work with uranium while Burton and Thompson have reported the latest work on plutonium. Their papers give a summary of all previous work and will be used for comparison here.

Examination of the three dimensional plots of slow neutron fission fragment energy for uranium and plutonium indicates that the topological features of the curium plot are the same. By this is meant the general shape and characteristics are identical. The following connection between slow neutron and spontaneous fission is worth noting. It is believed that slow neutron fission is really spontaneous fission of the original nucleus after it has absorbed a neutron. The binding energy of the neutron becomes energy of excitation of the new nucleus. Thus the new nucleus is highly excited and fission results. For example, when U$^{235}$ absorbs a slow neutron it becomes U$^{236}$ with the approximately 6.5 million electron volts neutron binding energy exciting that nucleus above the ground state. The resulting spontaneous fission of this new nucleus is termed slow neutron fission of U$^{235}$. The important fact is that what is normally called spontaneous fission is the splitting of a nucleus without this extra excitation energy.
It has been observed that as the atomic number of the fissioning nucleus or the incident neutron kinetic energy increases, neutron fission becomes more symmetrical.\textsuperscript{14,21,17,18} It might therefore be expected that spontaneous fission, due to its lower excitation energy, would be less symmetrical. The comparison of curium with plutonium or uranium is complicated by the fact that the atomic number is not the same.

It should be pointed out that the experimental results do not agree with the published theories.\textsuperscript{59,60,61,62} There is no adequate theory to explain the asymmetry of either slow neutron or spontaneous fission.

Since the work described in this report was first undertaken, three other groups have reported work on spontaneous fission.\textsuperscript{24,55,58} Weigand and Segre\textsuperscript{24} investigated plutonium.\textsuperscript{240} The Chalk River group examined curium\textsuperscript{242} (their tentative report consists of two paragraphs).\textsuperscript{55} Whitehouse and Galbreith studied natural uranium.

Weigand and Segre used a platinum plate with 17 micrograms of plutonium electroplated over a centimeter area. The single sided fragment energy distribution was observed and compared with the results from the slow neutron fission of plutonium\textsuperscript{239}. The statistics were not very good. The resolution was poor probably due to the lack of collimation. No detectable difference between spontaneous and slow neutron fission of plutonium was observed. The energy was measured by photographing the amplified ionization chamber pulse.

The Canadian workers used a sample with $4 \times 10^7$ alpha counts per minute with a collimator of $1/12$ transmission. It is believed that they used only a single sided ionization chamber. The energy was recorded by means of a ten pen recorder. They report high and low energy peaks at 95 and 65 million electron volts, respectively. They also report a valley more shallow than for Pu\textsuperscript{239}, but attribute this to instrumentation difference.
Whitehouse and Galbreith utilized a large cylindrical ionization chamber with 57 milligrams of uranium in a 100 microgram per square centimeter layer. No collimator was used but a self-absorption correction was made. A direct comparison with slow neutron fission was used for the calibration. No difference between spontaneous and slow neutron fission was reported.

The information on slow neutron and spontaneous fission is summarized in Fig. 46. It should be pointed out that the slow neutron figures are from experiments using pulse analyzers and have much better resolution than a photographic method. The results from uranium and plutonium have been linearly extrapolated to curium and are given in the table.

The positions of the high and low energy peaks reported here are higher than expected from the extrapolation and are also higher than the Chalk River results. The ratio of high to low energy peaks is near the expected value and the Canadian value high. This raises the question as to whether the calibration is correct or not. It should be pointed out that the ratio of the high to low energy peaks is an indication of the degree of symmetry of fission. The results reported here indicate curium spontaneous fission is more symmetrical than plutonium slow neutron fission.

It should be pointed out that perfect agreement between the various curium runs reported here is not to be expected. The equipment was slightly modified between runs. However, between the Cm$^{242}$-III and U$^{235}$-II runs nothing was changed except the sample. The gas circulating pump was removed half-way through the uranium run, but this did not change the distribution.

When a uranium sample is being used the fragments do not occur simultaneously in both parts of the chamber. With a curium sample they do. If any coupling, magnetic or capacitive, exists between the two channels it might alter the effective gain. Coupling effects have been looked for
Fig. 46. Table of Comparative Results for Spontaneous and Slow Neutron Fission.
### FIGURE 46

<table>
<thead>
<tr>
<th>Material</th>
<th>HE Peak</th>
<th>LE Peak</th>
<th>HE/LE</th>
<th>Total E</th>
<th>Z²/A</th>
<th>E_t/E_tU²³³</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th²³²</td>
<td>92.6</td>
<td>58.3</td>
<td>1.58</td>
<td>150.9</td>
<td>34.9</td>
<td>1.02</td>
<td>14</td>
</tr>
<tr>
<td>U²³³</td>
<td>91.2</td>
<td>55.5</td>
<td>1.64</td>
<td>146.7</td>
<td>34.8</td>
<td>1.00</td>
<td>17</td>
</tr>
<tr>
<td>U²³⁵</td>
<td>92.7</td>
<td>59.0</td>
<td>1.57</td>
<td>151.7</td>
<td>36.0</td>
<td>1.03</td>
<td>17</td>
</tr>
<tr>
<td>U²³⁸</td>
<td>See note</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>Pu²³⁹</td>
<td>93.3</td>
<td>63.9</td>
<td>1.47</td>
<td>157.2</td>
<td>37.0</td>
<td>1.07</td>
<td>18</td>
</tr>
<tr>
<td>Pu²⁴⁰</td>
<td>See note</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>Cm²⁴² (Extrapolated)</td>
<td>93.9</td>
<td>68.8</td>
<td>1.37</td>
<td>162.7</td>
<td>38.1</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>Cm²⁴² (Chalk River)</td>
<td>95</td>
<td>65</td>
<td>1.46</td>
<td>160</td>
<td>38.1</td>
<td>1.09</td>
<td>25</td>
</tr>
<tr>
<td>Cm²⁴² (Univ. of Calif.)</td>
<td>78</td>
<td>78</td>
<td>1.35</td>
<td>183</td>
<td>38.1</td>
<td>1.25</td>
<td></td>
</tr>
</tbody>
</table>

*Slow Neutron Fission.*

**Spontaneous Fission:** The statistics of this data are not very good. When compared to U²³⁵ or Pu²³⁹ no difference is reported outside of the expected statistical fluctuations.

***Fast Neutron Fission.*
visually, by use of the pulse generator and photographs, and by running the Cm$^{242}$-III sample one channel at a time. No detectable coupling was observed.

As a check on the equipment, after the data presented here was taken the Cm$^{242}$-III sample was again placed in the chamber. A short run was made and indicated the recording equipment had not changed. The U$^{235}$-II sample was then put back in the chamber and the results of a short run indicated that no change had taken place in the recording equipment. During these checks the gain suddenly changed by five percent and the change was detected with the pulser. Although the results agreed with previous data, if the gain change was considered, the almost completely dead tubes were located, changed and the data since the last gain check repeated. It should be pointed out that with feedback circuits all tubes should be checked before a series of runs is started. For example, all tubes were checked before the Cm$^{242}$-III — U$^{235}$-II series of runs were started. The only changes that were made are those indicated above.

The errors to be expected have been discussed previously. Only the self absorption, film absorption and alpha background errors are different for the uranium and curium runs. This difference should be less than two million electron volts. It is felt that the Chalk River results are probably low and the values reported here high. There is no experimental evidence to support this feeling; however, and the calibration has been left unchanged. It is expected that the accuracy of the measurements is plus or minus five million electron volts. This is roughly five percent. The disagreement with the Chalk River results is not explained.

It is clear that if these results are correct the kinetic energy release in the spontaneous fission of a Cm$^{242}$ nucleus is considerably greater than
that for the slow neutron fission of a $^{235}\text{U}$ nucleus. The binding energy of curium is known to be greater than the binding energy of uranium.

Seaborg has pointed out that if the results of these experiments are assumed to be five percent high, this fact accounts for most of the additional energy. If the division of the nucleus in fission remains the same in the two cases the curium will release a greater energy.

It is also possible, although not too likely, that the fission division changes so that the binding energy of the initial fragments are different or that the prompt neutrons or gamma-rays carry away a different amount of energy. As the symmetry of fission is changing, one might expect some change of total energy due to these effects. It is quite clear from the total energy release in fission that the energy is available for such changes.

These experiments have indicated the extreme importance of collimation and absorption corrections to fission data. They also indicate that the data on the initial ionization of fission fragments may not be correct. In this connection it should be pointed out that if the initial ionization data is incorrect both the sample thickness of sample $^{235}\text{U}$-II and the collimator used by the Chalk River investigators, the collimator thickness is not given, are more important than previously estimated. Both of these factors would tend to reduce the difference in observed results.

VI. SUMMARY

The energy distribution of the spontaneous fission fragments of curium$^{242}$ has been measured. Both fission fragments from a binary fission were measured simultaneously. The topological features of the distribution are the same as for slow neutron fission. The fission is more symmetrical than uranium or plutonium slow neutron fission. The total kinetic energy of the
fragments is greater than for slow neutron fission of plutonium. The 
increase is greater than predicted from simple considerations.

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Energy Commission.
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The following is by no means a complete reference to the literature on the subject of fission. However, insofar as is possible the original paper and the more recent papers on a topic have been given.


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