UNCLASSIFIED

N-1810 PHYSICS-GENERAL

INVESTIGATION OF NUCLEAR REACTIONS AND SCATTERING PRODUCED BY NEUTRONS

by

Raemer Edgar Schreiber

June 1941

Purdue University

Reproduced direct from copy
as submitted to this office

UNITED STATES ATOMIC ENERGY COMMISSION
Technical Information Division, ORE, Oak Ridge, Tennessee
AEC, Oak Ridge, Tenn., 3-20-50--94-A20258

UNCLASSIFIED

PURDUE UNIVERSITY

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION

BY Raemer Edgar Schreiber

ENTITLED Investigation of Nuclear Reactions and Scattering Produced by Neutrons

COMPLIES WITH THE UNIVERSITY REGULATIONS ON GRADUATION THESIS AND IS APPROVED

BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF

Doctor of Philosophy

Francis Horton — Professor in Charge of Thesis

Francis Horton — Head of School or Department

May 29 1944

TO THE LIBRARIAN:—

THIS THESIS IS NOT TO BE REGARDED AS CONFIDENTIAL.

Francis Horton
Professor in Charge

Registrar Form 19-5-20-1M

INVESTIGATION OF NUCLEAR REACTIONS

AND SCATTERING PRODUCED BY NEUTRONS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Raemer Edgar Schreiber

in partial fulfillment of the

requirements for the Degree

of

Doctor of Philosophy

in

Physics

June, 1941

Table of Contents

Page

I. Statement of Problem

A. Introduction ---------- 1

B. Neutron Scattering ---------- 1

C. Uranium Fission by Neutrons ---------- 7

II . Production of Neutrons

A. The Neutron Generator ---------- 11

B. Ion Source ---------- 14

C. High-voltage Supply ---------- 26

D. The Accelerating Tube ---------- 40

E. Target and Magnetic Analysis ---------- 49

F. Pumping System ---------- 52

G. Generating Voltmeter ---------- 54

H. Measurements of Neutron Production -------- 56

I. Detecting Apparatus ---------- 57

III. Investigation of Indium

A. Discussion ---------- 59

B. Procedure ---------- 60

C. Results ---------- 62

IV. Neutron Diffraction

A. Method of Focussing ---------- 65

B. Measurements with Boron Detector ---------- 72

C. Measurements with Dysprosium Detector ----- 74

V. Uranium Fission

A. Statement of Problem ---------- 82

B. Experimental Procedure ---------- 84

Table of Contents

Page

(1). Ionization Chamber and Linear Amplifier--86

(2). Voltage Supply for Ionization Chamber --91

(3). Current Amplifier and Recording Oscillograph ---------- 92

(4). Artificial Pulse Generator ---------- 96

(5). Preparation of Uranium Samples -------- 98

(6). Shielding ----------104

(7). Measurements on Recording Films -------111

C. Results from Fission Experiments

(1). General ----------114

(2). Calculation of Uranium Thickness ------120

(3). Single Particles from Slow Neutrons ---124

(4). Single Particles--Effect of Increased Neutron Energy ----------125

(5). Comparison with Total Ionization from the Foil ----------134

(6). Stopping Power Measurements ----------137

(7). Criticism of Results ----------139

(8). Summary of Results ----------142

VI. Acknowledgements ----------144

VII. References ----------145

List of Illustrations

Page

Fig. 1 ----------12

Fig. 2 ----------14

Fig. 3 ----------16

Fig. 4 ----------20

Fig. 5 ----------23

Fig. 6 ----------27

Fig. 7 ----------27

Fig. 8 ----------28

Fig. 9 ----------29

Fig.10 ----------30

Fig.11 ----------32

Fig.12 ----------38

Fig.13 ----------41

Fig.14 ----------41

Fig.15 ----------49

Fig.16 ----------55

Fig.17 ----------58

Fig.18 ----------67

Fig.19 ----------69

Fig.20 ----------71

Fig.21 ----------75

Fig.22 ----------75

Fig.23 ----------78

Fig.24 ----------85

Fig.25----------86

List of Illustrations

Page

Fig.26 ---------- 88

Fig.27 ---------- 89

Fig.28 ---------- 91

Fig.29 ---------- 93

Fig.30 ---------- 95

Fig.31 ---------- 95

Fig.32 ---------- 95

Fig.33 ---------- 97

Fig.34 ----------103

Fig.35 ----------107

Fig.36 ----------107

Fig.37 ----------112

Fig.38 ----------114

Fig.39 ----------115

Fig.40 ----------124

Fig.41 ----------127

Fig.42 ----------127

Fig.43 ----------135

Fig.44 ----------137

ABSTRACT

The construction and performance of a neutron generator consisting of a low-voltage arc and an accelerating tube is described. Deuterons are formed by ionization of heavy hydrogen gas in the arc source, focussed by an electrostatic lens system and accelerated by a Van de Graaff-type generator. When these ions fall on a target of heavy ice, neutrons are formed by the deuteron-deuteron reaction.

A study of the relative activities of the 54-minute and the 4.1-hour period of indium is made, showing that the latter period is activated principally by fast neutrons. Absorption measurements give a cross-section for resonance neutrons in indium which agrees with previous values.

Two separate attempts are made to detect the diffraction of neutrons, using a focussing method. Results are not conclusive because of high background and low intensities, but indicate that the diffraction intensities must be small.

The effect of neutron energy on the mode of uranium fission is investigated, using neutrons from the Be-D and Li-D reactions in the cyclotron, a special ionization chamber, linear amplifier and recording oscillograph. Plots of the number of pulses versus recoil energy of the fragments are made. With slow neutrons, an energy

distribution of single fragments agreeing with that of former investigations is found. With fast neutrons, three new modes of fission are assumed to exist: highly assymmetrical binary, symmetrical binary and symmetrical ternary.

By applying the law of conservation of momentum, it is possible to calculate the relative masses of the fragments in each case. The results agree with those obtained by using chemical analysis.

Using a uranium layer on a thin supporting foil, measurements on the total ionization are made. These agree with the energies calculated from the single fragments and correspond with those calculated theoretically.

The energy loss by single fragments which have traversed the supporting foil agrees closely with that calculated from the cross-sections given by Knipp and Teller.

FOREWORD

The principal topic of this thesis is the investigation of uranium fission by neutrons. At the request of Dr. K. Lark-Horovitz, director of the research, a rather complete description of the neutron generator and its auxiliary apparatus has also been given. This was done in order to compile the equivalent of a working manual for those who may be using this apparatus in the future.

As a result, the remainder of the paper following the introduction divides naturally into two parts: the description of the neutron generator and the experiments performed with it, and the discussion on fission.

I. Statement of Problem

A. Introduction. The investigations described in this paper deal with the properties of slow and fast neutrons and the reactions induced when they are used to bombard various materials. The two problems examined in greatest detail are: (1) The elastic and inelastic scattering of neutrons, particularly from a crystal surface, and (2) fission induced in uranium by neutrons, investigated as a function of the neutron energy.

It is proposed first to state the problems in some detail, giving the history of the developments up to the time when the research was started and some of the reasons why the investigations are of interest; next to discuss the problem of neutron production and give a description of the apparatus used. The detecting apparatus is next described together with some results of preliminary tests. The experimental procedure and results of the neutron scattering work is next given and the final sections deal with the investigation of uranium fission and discuss the results.

B. Neutron scattering. The scattering of neutrons by atomic nuclei is of great interest because such measurements give information regarding the nuclear binding forces. Neutrons are the most suitable particles for this work since they are uncharged and, accordingly, will not be affected by the Coulomb field of the electrons or of the

nucleus but will be deflected only when they approach the nucleus very closely and come within the range of the true nuclear forces.

A particularly interesting phase of this work is the possibility of coherent scattering of neutrons by atomic nuclei. This would correspond to the diffraction of electrons and x-rays--processes which have already been thoroughly investigated. According to deBroglie's wave-mechanical picture, associated with any moving particle is a wave packet of wavelength given by $\lambda = h/mV$, where λ is the wavelength, h is Planck's constant, m is the mass of the particle and V its velocity. In the elastic scattering of such a particle by regularly-spaced scattering centers, interference will take place between the incident wave and the scattered wave. If the conditions for constructive interference are fulfilled, large intensities of scattered particles should be observed. This theory has been thoroughly tested by electrons and has led to new methods of studying the structure of materials by the patterns formed by the diffracted electrons.

The electrons are scattered by the strong electrostatic fields existing around the atoms and never approach the nucleus closely enough to be affected by the nuclear forces. A heavier particle such as a proton or an alpha particle still is deflected principally by the electrostatic field of the nucleus, but a neutron, having no charge, will be deflected only by the nuclear forces. Another problem

arises when heavy particles are used because the wave-length varies inversely as the mass. This means that the velocity of the particle must be small. More specifically: Bragg's equation for the diffraction of a wave by a crystal whose lattice constant is d, is

$$n\lambda = 2d \sin \theta$$

where n is an integer equal to the order of the reflection and θ is the angle between the beam and the crystal plane. For most crystals, d is of the order of a few angstroms. This means that λ must also be of the order of one angstrom in order that θ may be large enough to measure. If one lets $\lambda = 1\,\text{Å}$ and inserts the mass of a proton or a neutron in the deBroglie equation and solves it for V, one finds:

$$v = h/m = \frac{6.6 \times 10^{-27}}{1.6 \times 10^{-24} \times 10^{-8}} = 3.7 \times 10^{5} \text{ cm/sec.}$$

This corresponds to 1.1×10^{-13} ergs or 0.07 electron-volts. The detection of single protons or alpha-particles of such energies is virtually impossible since they are recorded by their ionization and it requires about 30 eV. to produce one ion-pair. On the other hand, slow neutrons of this and even much lower energy are easily detected from the disintegrations produced by them in a large number of nuclei. Hence the observation of neutron diffraction would appear much simpler than of proton or alpha-particle diffraction.

It should be mentioned that specular reflection of hydrogen and helium molecules, which is a zero-order

diffraction, was obtained by Stern and his co-workers in 1932. Also, Yearian (Y-1), using protons of about 30 kv. energy and a long camera to permit the measurement of very small angles, found evidence for proton diffraction.

Three major items would result from an experiment on neutron diffraction: (1) Further verification of the deBroglie equation, or, assuming its correctness, a direct measurement of the velocity spectrum of slow neutrons; (2) the possibility of using the diffracted beam of neutrons as a monochromatic source for other experiments; (3) determination of the mechanism of nuclear scattering.

(1) On the basis of the deBroglie equation, one can at once calculate the velocity and energy of the neutrons which are scattered from a crystal of known lattice constants. Direct measurements of the velocity of slow neutrons from a radon-berryllium source surrounded with paraffin were made by Dunning and his co-workers (D-1), using a pair of rotating disks with cadmium sectors between the source and the detector. The disks were mounted some distance apart on the same shaft and each was adjacent to a similar stationary disk. If the time of flight of the neutron equalled the time for the disks to advance by one sector, the neutron would be intercepted. From the decrease in neutron intensity for a given speed of rotation, the velocity distribution is determined directly. The results showed a maximum intensity at a velocity of about

250,000 cm/sec. with an approximate Maxwell distribution, the intensity on the high-velocity side being higher than that of a Maxwell distribution because some of the neutrons had not been completely slowed down in the paraffin. The peak corresponds quite closely with the velocity predicted for thermal neutrons from the relation, E =3/2 kT. Their measurements were extended to neutron velocities of about 150,000 cm/sec. but were limited by the excessive speeds of rotation required.

Another approach to the same problem was made by Alvarez (A-1) and later by Fertel, Gibbs, et al. (F-1). The details of their methods differed but both used the same principle of producing the neutrons in short bursts and measuring the time required for the neutrons to travel to a detector located at a few meters distance. Recently, Baker and Bacher (B-1) and Haworth, Manley, Vore and Leubke (H-1) have improved the technique of this method to increase the precision and range of the measurements.

All of these methods require high-intensity sources and elaborate timing circuits. A direct check by measurements from neutron diffraction would therefore be most valuable.

(2) Slow neutrons (energies of a few electron-volts or less) are suitable for a wide range of experiments which lead to results of great theoretical interest. The Breit-Wigner theory of slow neutron processes (B-2) (B-3) is based on a nuclear model in which there are a number of

possible excited states. If the energy of an incident neutron coincides with the energy of such a state, the probability of neutron capture is particularly large and the absorption cross-section of a nucleus for such a resonance energy will be very large. In order to test this theory, one should make absorption experiments on slow monochromatic neutrons. Unfortunately, sources of such neutrons are not known. The best nuclear reactions for the production of neutrons ($H^2 + H^2$, $Be + H^2$, $Li + H^2$, $Be + He^4$, etc.,) yield neutrons of energies of several million electron-volts. If the neutrons pass through paraffin or other hydrogenous material they are quickly slowed down by elastic collisions until thermal energies (0.025 eV) are reached, but this is a statistical process and results in a wide spread of energies. (Cf. Dunning's experiment mentioned above). The selection of monochromatic neutrons by utilizing short neutron bursts, as already described, offers a solution to this problem but involves very elaborate apparatus. In principle, a crystal "monochromator", operating continuously, would offer a much simpler solution.

(3) Finally, there is the consideration of the mechanism of neutron scattering and the lifetime of the neutron in the scattering nucleus. This, possibly, should have been considered first since it determines whether or not neutron diffraction should be possible, even in principle. According to the concept of the compound nucleus, as

proposed by Bohr, nuclear processes are initiated by the entrance of the bombarding particle into the nucleus, forming a compound nucleus. The energy of the incident particle is then shared among the several nuclear particles and there is a free competition among them as to which will attain sufficient energy to overcome the potential barrier and escape. In the case of neutrons, if the particle re-emitted is a proton or an alpha-particle or if the energy is dissipate. as a gamma-ray, the neutron is captured. If the neutron is re-emitted, but part of its energy dissipated by emission of a second particle or a gamma ray, it will have a changed wavelength and cannot show interference effects. Only if the neutron is re-emitted with no loss of energy, can it exhibit interference phenomena. On the other hand, if the scattering takes place without the neutron's actually entering the nucleus, there is no chance for an energy loss and strong interference should be observed. Hence, even a negative result from a neutron diffraction experiment will prove valuable in deciding which of the above theories is correct. Mitchell and Powers (M-2) and Von Halban and Preiswerk (V-1) have obtained qualitative results which indicate the existence of diffraction, but those results are not entirely conclusive.

C. Uranium fission by neutrons. In 1939, Hahn and Strassmann (H-2), after a careful and exhaustive series of

experiments, announced that uranium, bombarded by neutrons, split up to form isotopes of masses in the neighborhood of 140 and 100 and identified these as isotopes of barium and lanthanum and strontium and yttrium, respectively. This discovery was of great importance, first, because it removed all the accumulated difficulties of the "trans-uranic elements" which had been disturbing physicists for several years, and second, because this was the first case of an atomic transmutation which resulted in the splitting or fission of the nucleus into two massive parts. Following the announcement of the fission of uranium, experimentalists all over the world set to work on this problem and soon accumulated a great mass of data. On the theoretical side, Bohr and Wheeler (B-4) developed the theory of fission based on the liquid-drop model first proposed by Meitner and Frisch (M-1) who also suggested the word "fission" to describe the process.*

According to the liquid-drop model, the nucleus is in equilibrium under the action of two groups of forces: the short-range nuclear forces which have an action analogous to the surface tension forces of a liquid drop, and the repulsive forces due to the electrostatic energy of the protons. If the surface forces predominate, the most

# # # # # # #

* It is not proposed to attempt a comprehensive summary of the present state of the problem of fission here, rather, only a brief sketch of aspects pertinent to the research to be described later will be given.

stable shape will be that of a sphere, but as the nucleus becomes heavier and more highly charged, the electrostatic forces play a larger role and the nucleus approaches instability. If the nucleus is now given a finite distortion, fission can occur. Bohr and Wheeler calculated this problem in detail and showed that for protactinium, thorium and uranium the critical energies to produce fission were of the order of 5-6 Mev. If the excitation is by a neutron, the same calculation must be made for the compound nucleus thus formed and yields much lower values, being -1.2 Mev. for U^{235}. This means that a thermal neutron can produce fission of this isotope. The values for U^{233} and Th^{232} are 0.7 and 1.7 Mev. respectively, so these should undergo fission only with fast neutrons. This has been verified experimentally in the case of Th and is usually assumed to be true of U^{238}.

The theory has not yet been developed to the point where the relative size of the two fission particles can be predicted but indicates that quite a range might be possible depending on the various modes of vibration which are excited. Of particular interest to the present research are the following data:*

(1) The energy release per fission, as measured by various methods, leads to a value of 160-180 Mev. Most of these measurements are based on ionization processes.

# # # # # # #

* A detailed compilation has been made by Turner (T-1) for publications prior to December, 1939.

(2) For slow neutrons, the two fragments are of unequal size. The radioactive isotopes observed fall into two groups; one with atomic numbers between 35 and 43, and the other with atomic numbers between 51 and 57. The asymetrical fission leads directly, with the law of conservation of momentum, to different energies of recoil for the two fragments. Kanner and Barschall (K-1), using a linear accelerator to produce D-D neutrons and an ionization chamber to record the sizes of the pulses, found these energies to be 65 and 98 Mev, respectively. Jentschke and Frankl (J-1), using slow neutrons from a polonium-berryllium source, obtained somewhat lower values of 57 and 93 Mev.

(3) The distribution curves of number of pulses observed vs. energy indicate rather broad maxima at the energies cited above with a valley between the two peaks of about one-half peak height. This correlates with the chemical evidence that there are groups of isotopes of various masses formed in each case instead of a single predominant isotope.

(4) Yasaki (Y-2) found that the isotopes of intermediate atomic number Pd(46), Ag(47), Cd(48), and In(49) were observed in addition to the isotopes mentioned above if the neutrons used were the extremely fast ones (13.6 Mev. reaction energy) from the reaction of deuterium on lithium. If Be-D neutrons were used, the intermediate isotopes were not found. This indicates that a more symmetrical fission

of uranium can be obtained if very fast neutrons are used.

The purpose of the present investigation of fission is to study (1) the energy of the single particles from the fission of uranium as a function of the incident neutron energy; (2) the total ionization of the recoil particles as a function of the incident neutron energy; (3) range-energy and stopping-power relations for fission particles. Further discussion of these problems will be given later in connection with the experimental results.

II. Production of Neutrons

A. The neutron generator. When this research was started, there were no neutron sources in the laboratory so the production of neutrons became the immediate problem. The possibilities were: (1) Purchase or rental of a quantity of radium which could be mixed with beryllium powder to utilize the reaction of alpha particles on beryllium; (2) use of a beam of accelerated ions to produce neutrons by deuteron bombardment of deuterons, beryllium, or lithium. The second alternative was chosen because the amount of money available for the work made the purchase of the radioactive materials prohibitive and would allow the rental of only a small amount of material. (200 mg. of radium mixed with beryllium powder can be rented for minimum periods of one year at an annual rental of $1000). This would definitely limit the type of work possible.

The equipment chosen after some consideration of the

various possibilities was a linear accelerating tube using a low-voltage arc source and a Van de Graaff-type generator as the source of high potential. This unit will henceforth be referred to as the "neutron generator". This choice was dictated partly for reasons of economy and partly because it offered the most flexible unit to be built in the space available. Much higher intensities would be available with a cyclotron of the size now operating in this laboratory but both the cost and the time of construction are large. A Cockroft-Walton or similar transformer-multiplier unit might be used as a high-voltage source in place of the Van de Graaff generator but the cost again is greater and other laboratories have had difficulties in achieving voltage outputs which even approach the calculated values.

The setup which was evolved for the neutron generator is shown schematically in Fig. 1. (The photograph of Fig. 2 is taken from a direction indicated by the arrow in Fig. 1).

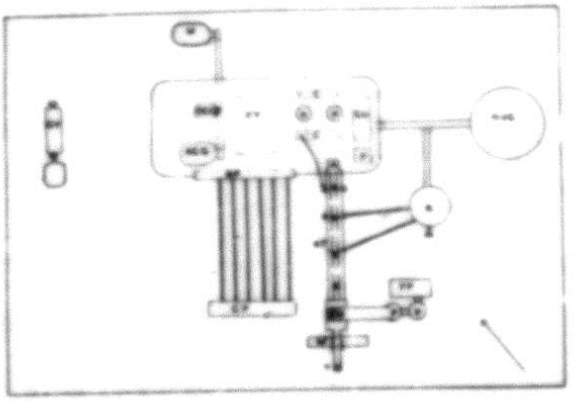


FIG.1 - PLAN OF NEUTRON GENERATOR

Fig.1--Plan view of neutron generator

The ion source and power supplies are housed in a cylindrical aluminum shell which is mounted on porcelain insulators. The high-voltage generator (HVG) is placed beside this housing in a 2½ foot pit (because of restricted vertical clearance) and is connected to it by a 3" copper tube. The accelerating tube (AT) extends from the housing to a concrete pier (not indicated) which supports the electromagnet for magnetic analysis (M'), the pumps (P) and the target assembly (T). Power for the ion source (A) and focussing voltages is supplied by a 2 H.P. motor (M) on the floor which drives a 1500 watt A.C. generator (AGG) in the housing by an insulating belt. Fiber rods extending from the control panel (CP) to the meter panel (MP) provide the controls for the various circuits. Meters for arc voltage and current, etc., are mounted in the meter panel and can be read from the control station back of CP. Copper mesh is placed over the meters to provide electrostatic shielding. The resistance stack (R) is used to divide the accelerating voltage between the several electrodes (E).

A small D.C. generator (DCG), driven from AGG by a V-belt, supplies 110 volts to the arc. A low-voltage transformer (F) supplies the arc filament. FT, C and K represent the transformer, condensers and kenetrons of the supply for the focussing. A cooling unit (CU) for the arc circulates water in a closed circuit between the arc and a pair of auto-heater radiators where the water is

cooled by a blast of air.

The voltage measurements are made with a Kirkpatrick-type generating voltmeter (GV) driven by a synchronous motor.

The pumping lead is at the grounded end of the accelerating tube. Two 4" metal oil-diffusion pumps in series (P,P) are connected to the accelerating tube through a gate valve (GV) which permits one to open the tube for adjustments without shutting down the pumps. A megavac pump located on the floor below the diffusion pumps produces the fore vacuum.

The various items mentioned here will be shown and discussed in further detail later.

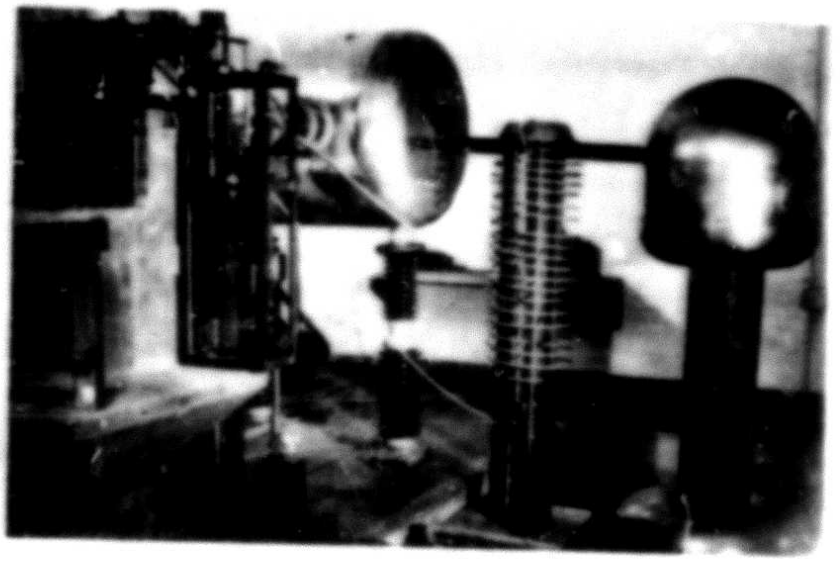


Fig. 2--View of completed neutron generator

B. Ion Source. Two different types of ion sources have been used in the neutron generator. The first one was of

the capillary type as developed by Tuve (T-2). Its construction is shown in the line drawing of Fig.3. An arc is formed between the steel anode (1) and the oxide-coated filament (2). This arc is constricted by passing through the 3 mm. diameter capillary in the steel arc body. A channel drilled at right angles to the capillary permits the positive ions to drift out into the field of the steel probe (3) which is maintained at -1500 to -3000 volts with respect to the arc body. The probe has a canal 1 mm. in diameter and 4 mm. long through which the ions pass after the initial acceleration in the probe gap.

The general method of construction is apparent from Fig.3. The filament shown consists of a double hairpin of 15 mil tungsten wire wound with a single layer of closely-spaced 3 mil nickel wire. The purpose of this piano-wire construction is to provide a large area for the oxide coating and to provide the numerous crevices which appear to be most effective sources of electrons from oxide-coated cathodes. The coating is a commercial strontium-barium suspension obtained from Callite Products, Inc. It is applied to the cold filament with a brush and allowed to dry. It is then heated until colored a light brown. Three coatings are usually applied. At first, the heating was carried out in a CO_2 atmosphere but this was found to be unnecessary and the filament merely heated in the open air.

The oxide coating evolves considerable gas when first

heated in a vacuum so the filament is usually warmed slowly and run at reduced current for 10-15 minutes before attempting to obtain any emission.

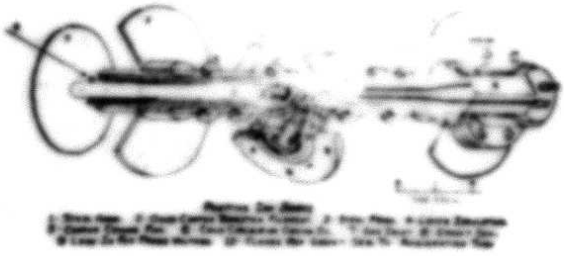


Fig. 3--Tuve-type ion source.

Typical procedure in activating such a 15 mil tungsten filament is the following: After coating filament and heating in air, it is installed and the tube pumped down. The filament is turned on and held at a current of about 5 amp. for 10 to 15 minutes. The current is then gradually increased to about 9 amperes and the arc voltage applied. Activation will then usually take place within 5 minutes. Enough residual gas is usually present in the ion source to cause the arc to strike. When the arc becomes stable, the filament current can be reduced to about 7.5 amp.

Other sizes and shapes of filaments have also been used with good results. The filament which had the best characteristics was made of 15 mil tungsten, 3" long, wound in a conical helix with the vertex away from the capillary. 25 mil tungsten was also used but requires a

current of 15 amp. for activation and 13 amp. for steady emission and was more difficult to shape. The coating and activation procedure is the same for the various shapes.

For ease in starting the arc, the arc body is connected to the anode through a 1000 ohm resistance. Under almost any operating conditions, an arc will then form to the body and this helps in igniting the main arc through the capillary. It was also found helpful to slip a sleeve of thin mica into the arc body so it surrounded the filament and prevented a direct arc to the wall of the arc body. No difficulty was experienced in maintaining the discharge through the capillary if the filament emission was sufficient to start the discharge. Few measurements of the electron emission were attempted because there was usually enough gas in the ion source to produce an arc as soon as the emission became greater than 100 ma.

Gas (usually deuterium or hydrogen) to supply the arc is stored in a 1-liter glass flask and admitted to the ion source through a compound needle valve of a type used extensively in this laboratory. This needle valve was developed by Mr. H. A. Hurd, of our instrument shop. The needle is moved by the combined action of two screws, one right and one left-hand. The differential action can be adjusted by selecting the ratio of the pitches of the two screws.

The operating characteristics of the ion source do not lend themselves well to precise analysis since the

output current of positive ions depends on at least four variables which are themselves somewhat interdependent: filament current, arc current, arc voltage and probe voltage. In practice, it is found that for a given probe voltage there will be an optimum arc current and arc voltage and that the output will drop for both higher and lower values. Further, the probe voltage determines the focussing properties of the ions, and the arc voltage, being a function of the gas pressure, is connected with the percentage of protonic ions produced. Hence, while it was instructive to make measurements on ion output as a function of the several variables, it was simpler in practice to adjust the apparatus for best performance by trial and error, using the measurements only as a rough guide.

Best ion output was obtained with an arc current of 0.9 amperes, filament current of 7.5 amperes, arc-voltage drop of 90 volts and probe voltage of 2400 volts. This gave a focussed beam of 280 microamperes through the first focussing electrode.

In view of the limited current available from the high-voltage generator, it was important to obtain a large percentage of protonic ions in order to get the largest possible neutron yield. Measurements made on the deuteron beam after acceleration, using the magnetic analyzer, gave only 15 to 20 percent D^+ ions. This seemed to be approximately independent of the operating conditions excepting

only that the percentage decreased with increased total current. These measurements are in agreement with those of other investigators on metal-capillary ion sources.

A study of other available types of ion sources was made in an attempt to improve this yield of protonic ions. All modifications of the metal-capillary types showed essentially the same behavior: large percentages at small total currents of the order of 50 microamperes, and much smaller percentages for the larger currents of 300 to 400 microamperes desired for this work. The modification developed by Zinn (Z-1) gives currents up to 4.5 milliamperes but is not suitable because the protonic yield is again only 15 to 20 percent. Bradbury and Bloch (B-5) modified the ion source developed earlier by Lamar and Luhr (L-1), using a pair of concentric cones to focus the emergent beam, and succeeded in obtaining currents of 100 to 200 microamperes with approximately 40 percent protonic icns. This source appeared to be promising except for the rather limited current.

The only ion source, other than the original Tuve type, which has been constructed and tested is one based on a design developed by Prof. R.D.Fowler, of Johns Hopkins, who was kind enough to furnish plans and specifications for it. The design has not been published. This source was not installed until near the end of these investigations but will be described at this time.

A section through the ion source is seen in Fig.4.

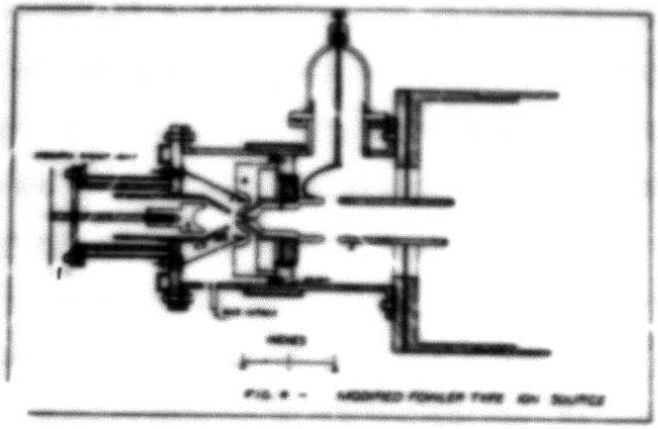


Fig.4--Sectional view of Fowler-type ion source.

The arc is formed between the ring-shaped filament (FF) and the anode (A). The discharge must pass through the annular space between the arc constrictor (C) and the probe shield (S). Thus a dense cloud of ions must be present in front of the probe canal and will drift through the hole in S to be acted on by the field from the probe (P) which is maintained at 6000 to 20,000 volts negative with respect to S. The filament is made of a platinum ribbon .003" thick, ½" wide and about 3" long. Before mounting, the ribbon was first run between a knurling tool and a brass rod several times and then folded accordian-fashion to form a rough surface for the oxide coating and to make its length adjustable. Three supports of 40 mil nickel were then spot-welded to the platinum and these were bent to fit into three brass mounting posts. These posts are not shown in detail on the drawing but each consists essentially of a nut and bolt mounted in an over-

size hole. A mica washer on the inner surface provides insulation and a rubber washer on the outside provides insulation and forms a vacuum-tight seal.

The anode is threaded on a steel rod and can be screwed in or out. Its position is not critical. It is insulated from the arc body with a gasket joint. The arc constrictor is made of steel and is also threaded. Its distance from the probe shield is quite critical. The distance should be the smallest which will still maintain the arc since this annular gap serves the same purpose as the capillary in the Tuve-type arc in concentrating the discharge. A clearance of 3/32" was found to be suitable.

The shape of the face of the probe shield proved to be a very important factor in the performance of the arc. The shape shown in Fig.4 was found to be the best of several tried. This appears to allow the formation of an ion sheath which is not easily "punctured" by the field of the probe. The ion output was decidedly less with both a more pointed nose and a flatter nose with a conical depression in the middle.

This type of arc source requires unusually high probe voltages. Fowler also found that the highest protonic yields were also found for quite high gas pressures (.15 to .3 mm of Hg) so the problem of preventing sparking between the probe and the probe shield becomes acute. This problem was solved by keeping all distances in the direction of the field of the order of

1 mm. Within the range of arc pressures used, the ionization over such a short path is very small and there is less difficulty with breakdown than there would be for a larger gap. The probe is threaded inside a lava ring which is threaded, in turn, into the arc body. The connection for the probe, as indicated, is made by a thin brass rod carrying a thin strip of phosphor-bronze which makes a flexible contact with the outside of the probe. Insulation is provided by the glass cylinder. There are wax joints between the rod and glass and between the glass and its supporting flange. The gasket joint is provided in addition so that the entire assembly may be quickly removed for inspection of the alignment of the probe and the first focussing electrode (M).

The current for the filament is supplied by a 6-volt, 20-ampere transformer with a series resistance in the primary. The platinum filament is usually run at 18 to 19 amperes and activated at 23 amperes. The activation current overloads the transformer somewhat, but this is only for short periods of time.

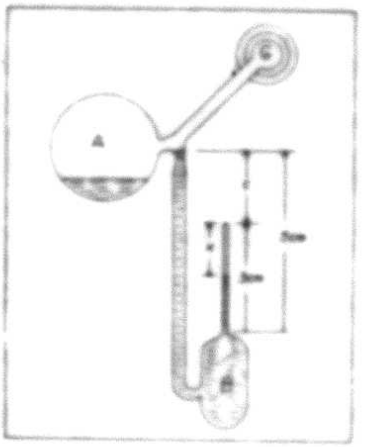
The arc voltage is supplied by a 300-watt, 120-volt D.C. generator which is driven by a V-belt from the shaft of the main generator. A series resistor permits a range of arc currents between .3 and 2.5 amperes.

Two different supplies for the probe voltage have been used. The first testing was done with a half-wave circuit using one-half of the secondary of the focussing-

voltage transformer. This hookup did not permit the independent adjustment of probe and focussing voltages, however, so was replaced by a half-wave circuit supplied by an 8000-volt R.M.S. transformer whose primary voltage was controlled by a potentiometer arrangement.

The gas pressure in the ion source is measured by means of a small tilting McCleod gage which is mounted in a ground joint and connected to the gas supply line. The gage itself consists of a small bulb with a capillary sealed into its top and a side tube connecting with a mercury storage bulb and the ground joint. Fig.5 shows the construction.

The gage is normally tilted counter-clockwise with all the mercury stored in bulb A. To take a pressure reading, the gage is rotated somewhat past the position shown until bulb B is filled, then returned to the vertical position. From the height of the capillary and an application of Boyle's law, the pressure is easily calculated from the measured height X. If C and X are the distances shown in the figure, a is the cross-sectional area of the capillary and V_0 is the volume of the gage the pressure is calculated to be $P = (C+X)aX/V_0$ mm. of Hg.



TILTING McLEOD GAGE

Fig.5-Tilting McCleod Gage

For the particular gage constructed, C= 30 mm., a = 2.4 mm^2, and V_0= 13,350 mm^3. For X equal to 10, 20, and 30 mm., respectively, this gage then indicates pressures of 0.07, 0.18, and 0.22 mm. of Hg. This covers the range of pressures to be used in the arc, then, with a capillary of only 30 mm. length.

Certain precautions must be observed in constructing the gage. There must be a constriction in the tube just below the opening into the storage bulb A to insure that the mercury will form a continuous seal when the gage is being filled. The opening into A should have a definite lip since the height of the mercury column in the supply tube is determined by this point. The offset of the whole gage from the ground joint G and the angle at which the storage bulb is joined to the supply tube must be such that the mercury will not spill out of the gage and into the ground joint when the gage is being emptied. Also, the lower bulb must be designed so that all the mercury will run out when the gage is tilted up for emptying.

The accuracy of such a gage is probably not very great. However, successive measurements have indicated that the heights are reproducible within a millimeter. The pressures are marked on a small card which is clipped to the gage back of the capillary so that a pressure reading can be taken in a few seconds.

The first tests of the Fowler-type arc were most unsatisfactory. The arc was very difficult to start, ion

currents were small and the filament lasted only a few hours before needing a fresh oxide coating. Part of the difficulty was finally found to be due to an intermittent leak in a soldered joint which accounted for the short filament life, but this still did not clear up the whole trouble. Prof. Fowler finally indicated that the original design which he sent had not shown the shape of the probe shield in sufficient detail and that he had also found a shorter probe-canal length to be more suitable. (Fig.4 gives the corrected design). These changes improved the performance a great deal.

Work on uranium fission with neutrons from the cyclotron was started before the ion source had been completely tested and it seemed more important to concentrate on the fission work, so the following results must be taken as tentative: The total available current from the ion source can be made very large, 2 to 3 milliamperes, but the ions are not well focussed under these conditions. A well-focussed beam of 200 microamperes was obtained, however. The measurements were made by grounding the probe, allowing the ion source to float at a positive potential and measuring the current collected by all the electrodes in the focussing and accelerating system. With an arc pressure of .28 mm., arc current of 1.0 amp., arc drop of 40 volts, and probe voltage of 4500, a steady current of 200 microamperes was obtained. Increasing the probe voltage increased the beam intensity greatly but

gave it a very bad divergence. This could be overcome somewhat by strong focussing at the next gap. The total output was quite satisfactory, but magnetic analysis of the accelerated beam showed only 20 to 25 percent protonic ions, as with the Tuve-source. This does not confirm the results which Fowler obtained with his original design which indicated 60 percent protonic ions at the gas pressure used in these tests. It may be that minor changes in design have a greater effect than suspected.

Mention should be made here of work now being done by Getting (G-1) and (G-3) and by Lamar (L-2) with glass capillary sources. The results already obtained indicate that this type of arc is capable of both large currents and high protonic yields.

C. High-voltage supply. When the neutron generator was first constructed, it was tested by using a large disk-type electrostatic generator which is used for demonstration purposes in the general physics lectures. When properly dried, this generator was capable of producing about 100 microamperes at 100 KV. With this available power, it was possible to demonstrate the production of neutrons but it was apparent that the neutron intensity was too small to permit the type of experiments desired. Some discussion has already been given to indicate the reasons for the choice of a Van de Graaff type of electrostatic generator for the new high-voltage source. Of the several modifications of this generator which had been developed,

that of Getting and Fiske (G-1) appeared to be the most suitable both with regard to compactness and available current. Dr. Getting very kindly furnished complete specifications for the apparatus before publication of his results and was of great service in many other ways, loaning patterns for the various castings and assisting us in obtaining the special spinnings required.

Fig. 6--Schematic drawing of high-voltage generator.

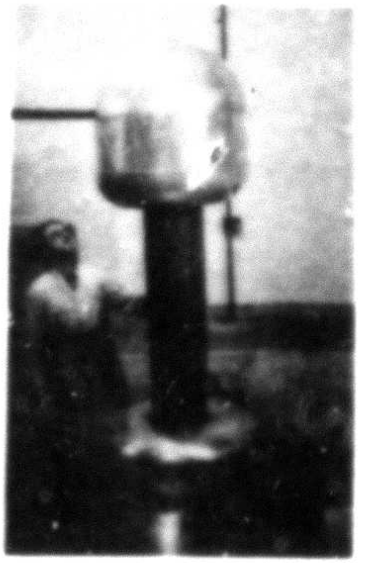


Fig.7--View of completed generator.

The general construction of the high-voltage generator (HVG) is shown in Fig.6, and the appearance of the assembled generator is shown in the photograph of Fig.7. Three belts are used to carry the charge to the upper electrode, the middle belt running counter to the outer two. The use of multiple belts instead of a single wide belt makes the outfit more compact and permits placing belts inside the

insulating textolite column where they are protected against dust and humidity. By running the middle belt counter to the other two, higher charge densities can be obtained since the middle belt then carries the opposite charge to the others and reduces the transverse electric field. The belts are driven at a linear speed of about 90 feet per second by a 2 H.P. 3500 RPM motor mounted on a belt-tightening support in the base of the generator. Also in the base of the generator are a 10,000-volt rectified supply for the spray voltage and a cooling unit. The motor drive and the spray supply can be seen in Fig.8.

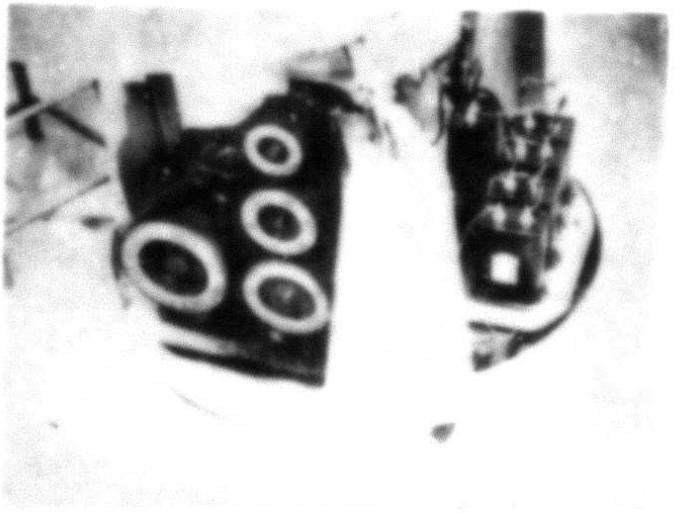


Fig. 8--Base of generator with shielding removed.

The upper assembly is supported by a textolite tube 12" in diameter with 3/16" wall. This tube is gripped at the bottom by a three-piece casting which is supported in turn by three tapered channel irons welded to the steel

base. The channels and a section of the column support can be seen in Fig.8. A ring-shaped aluminum casting is driven over the top of the textolite column and is held in place by several bakelite screws. The under-side of this casting is turned to fit the curve of the reentrant aluminum spinning which forms the bottom of the upper shield. Studs screwed into this casting support a second aluminum ring which carries the long studs on which are mounted the three upper pulley supports. These can be seen in Fig.9. The tension and tracking of each charging belt can be adjusted independently by means of nuts on these long studs. The pulley support rings have oversize holes and are fitted with phenolite sleeves which slide on the threaded studs. A phenolite washer on either side of the support ring completes the insulation of pulleys: required for the current-doubling arrangement. Soft rubber washers are also inserted on either side of the ring. These serve to damp out mechanical vibrations.

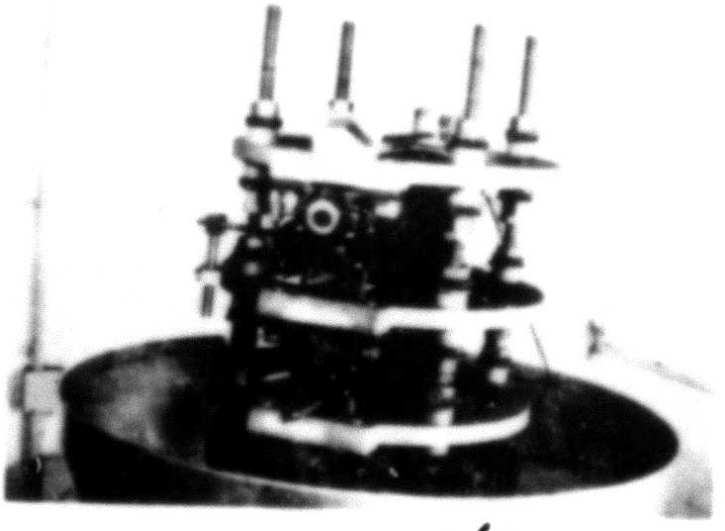


Fig.9--Upper assembly of generator with shielding removed.

The belts are of four-ply endless-woven cotton fabric manufactured by the A.S.Brown Co., Tilton, N.H. They have a special treating which is intended to cut down surface leakage under humid conditions. In spite of this treatment, it was not found possible to obtain steady currents from the generator under most weather conditions without keeping a drying agent inside at all times. These belts are much heavier than rubberized sheeting or paper sometimes used for this type of generator and therefore require a larger driving power to overcome flexing losses. This disadvantage is far outweighed by their durability, resistance to puncture by sparking and ease in alignment. The original set of belts is still in use and shows no apparent signs of wear.

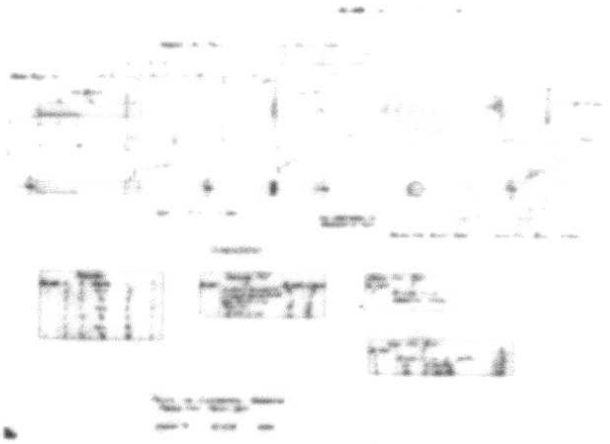


Fig.10--Design of charging-belt pulleys for generator.

SKF self-aligning roller bearings are used on all the pulleys. Each pulley shaft has one free bearing and

one fixed bearing, i.e., only one bearing on each shaft holds against end-play. This follows approved practice. The pulleys were constructed in the department shop with rollers of seamless steel tubing, turned inside and out, and shafts of 3/4" cold-rolled steel. Getting's original design indicated pulley construction using a plug and stub shaft welded into each end of the roller but a design using a full-length shaft was thought to be less liable to flexing and distortion at high speeds. Accordingly, the design indicated in the working drawing of Fig.10 was worked out by W.A.Miller and H.A. Hurd.

After the pulleys had been completed, the bearings were locked on the shafts, the Rockwood driving pulleys fastened in place, and the pulleys sent to the Gisholt Machinery Co. to be dynamically balanced. The top pulley of Fig.8 shows some of the holes where material was removed in the balancing process. That the dynamical balancing was essential was shown by a test in which the smallest roller, 3-inches in diameter, was rotated at 7000 R.P.M., its normal operating speed. In spite of the fact that it had been carefully machined, it vibrated very badly and was very noisy. The balanced pulleys showed no such behavior.

The power supply circuit is shown in Fig.11. As is indicated, it consists of a simple half-wave rectifier controlled by a Variac in the primary of the high-voltage transformer. The control box was located on the main

control panel of the neutron generator. The spray points consisted of a row of phonograph needles (Victor "Loud") set into a brass rod at 1/2" intervals. These were set directly below the corresponding pulleys and can be seen schematically in Fig.6. The brass rods were supported by slotted bakelite plates and could be adjusted for spray-point-to-belt distances of 0 to 3/4". The power supply itself is housed in the base of the generator and can partially be seen in Fig.8. The 10,000-volt transformer is located behind the tapered channel next to the pulleys. The rectifier and condensers were mounted on a transite base and this was placed on a rubber mounting to minimize mechanical vibration shocks.

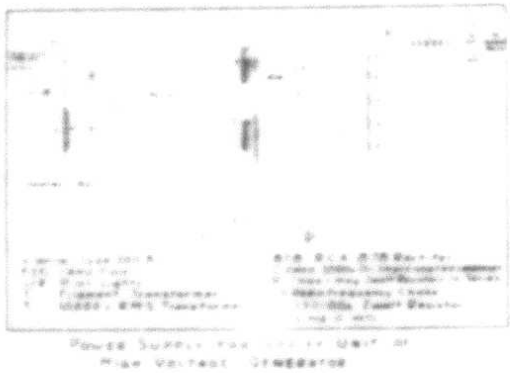


Fig.11--Power supply for spray unit of generator.

The collecting electrodes in the upper assembly had a construction similar to the spray electrodes and were also adjustable. As seen in Fig.9, they are located directly above the corresponding pulleys. The additional

electrode, barely visible inside its aluminum shield, is the current-doubling electrode and is connected directly to the pulleys. It is adjustable both vertically and horizontally. The three collecting electrodes above the pulleys are connected to the upper electrode through megohm resistances.

The function of the current-doubling electrode may be explained as follows: We will assume a positive high-voltage potential and consider the generator short-circuited to ground through a milliameter. If the spray potential is V, the outer surface of the belt as it leaves the lower pulley is V and the inner surface is at pulley potential, or zero. When the charged belt is opposite the doubling electrode, a brush discharge occurs to it and it acquires the potential V which is also communicated to the pulleys. When the inner surface of the belt contacts the pulleys, it then has the potential V so the outer surface must have the potential V+ V = 2V. The brush discharge to the collector electrode--and to ground--will then occur until the outer surface of the belt approaches zero and is at -V with respect to the inner surface. As the belt returns to the lower pulley, the inner surface must acquire zero potential and the outer surface must approach -V with respect to ground. If the capacitance of the belt (per unit area) is C and it acquires a charge Q with a potential difference V between inner and outer surfaces, one sees at once that a charge

2Q is required to restore the outer surface of the belt to its original potential of V, i.e., it carried a charge +Q up and a charge -Q down. If the doubling electrode were not used and the pulleys connected to the upper electrode, the downward-moving belt would be uncharged and would carry only a charge Q in one round trip. It has been assumed here that the brush discharges provide a short-circuit between belt and electrode, which is not, of course, strictly true. Also, the argument is restricted to the case of the short-circuit current with upper electrode grounded, but the reasoning is actually true in general since only the potential differences between the inner and outer surfaces of the belts, enter. Finally, no account was taken of the current drawn by the doubling electrode. If the insulation between the upper pulley supports and the shell is good, this current is negligible. under steady conditions after the initial charge has been drawn to give the pulleys their positive potential.

Before considering the performance of the generator, several other items of the construction should be mentioned. The main drive belt is subjected to severe flexing, an atmosphere highly charged with ozone and to moderately high temperatures (under continuous running). The first belts tried failed after some 40 hours running under these conditions. These belts were also of the endless-woven type and were made of heavy-duty four-ply material. The coating was a black non-skid preparation (treatment

HT49). This coating seemed to be one cause of the trouble since it became gummy and was thrown off the belt when it became warm. Later the belt would show broken strands and required replacement. The manufacturers were unable to find the trouble but suggested a lighter belt (medium four-ply) with a SCTLR coating. This was tried and found to be very satisfactory, the original belt of this type still being in use.

The 2 H.P. driving motor runs under approximately full load and most of this power is dissipated inside the generator, since the output of the generator is only of the order of 300 watts (1 ma., at 300 KV.). A good share of this power is used in maintaining belt speed against air friction and internal flexing losses. Consequently, the interior temperature of the generator rises steadily on long runs. The housing of the generator is purposely made nearly air tight to keep the humidity low and the polished surfaces of the aluminum provide poor radiators so it was necessary to introduce a cooling mechanism. An auto-heater radiator carrying cold water was first tried, using ar electric fan to circulate the air. This was inadequate so was supplemented by a system of four 1/4" copper tubes spaced about one inch apart which were bent to form a circle fitting just beneath the reentrent aluminum spinning of the lower housing. About 100 copper fins were soldered to these tubes to increase the cooling action. Cold water was circulated through the tubes.

Finally, it was found necessary to cool the textolite column and this was done by directing a blast of air from a rotary blower on the outside of the column. With this combination it was possible to run continuously without overheating.

A strong decrease in output current and available voltage is found if the interior of the generator becomes moist. To prevent this, several containers of silica gel are kept in the base and the upper electrode. A tubular heating element is also placed in the base near the electric fan and is run at reduced current when the generator is idle. This keeps the generator a few degrees above room temperature at all times, further reducing the relative humidity. A relay controlled from the main panel turns off the heater and turns on the blower when the generator is started. The fan is kept running at all times.

After the generator had been assembled, the belts were aligned by adjusting the upper pulley supports and were run idle for some time to wear in the bearings. These showed some tendency to heat at first due to friction between the shaft and the felt packing glands but this was soon overcome. The adjustment of the spray and collector points was next made by measuring the short-circuit current for the various spacings. Brass strips 1/4", 5/16", 3/8", and 1/2" thick were used between the electrodes and the belt to measure the clearances.

The process of adjustment was one of successive approximations since the optimum spacing of one electrode was dependent on the spacings of the others. The final spacings used were: 5/16" on the two lower spray electrodes and 3/8" on the upper one (smallest pulley); 1/4" on all collector electrodes, and 5/16" on the current-doubling electrode which was adjusted vertically to be about 2½" below the point of targency between belt and pulley.

The short-circuit currents were never greater than .5 ma. on the first tests. This current was finally increased to 1.0 ma. after several weeks during which drying agents were kept in the generator, the original 8000-volt spray-supply transformer was replaced by a 10,000-volt unit, a brass ring was inserted in the joint between the column support and the column to eliminate a sharp corner, and the insulation between the studs and the upper pulley-support rings was improved.

Even in dry weather, the output current of the generator is low for 24 hours or more after it has been opened. The current is also low when the generator is first started and will reach a steady value only after running for approximately one-half hour to warm up.

The variation of short-circuit current with spray voltage is shown in the curve of Fig.12. The abscissa is the primary voltage of the transformer. The true maximum spray voltage corresponding to 115 volts on the primary is about 13,000 volts. From the figure, one sees

that the curve is flattening but still increasing. At the maximum voltage, however, some sparking occurs. For continuous runs, 105 volts on the primary is set as an upper limit since there is some danger of puncturing the belt at higher voltages. With this limit, the maximum current from the generator is between 850 and 1000 microamperes, depending on the relative humidity and the condition of the column.

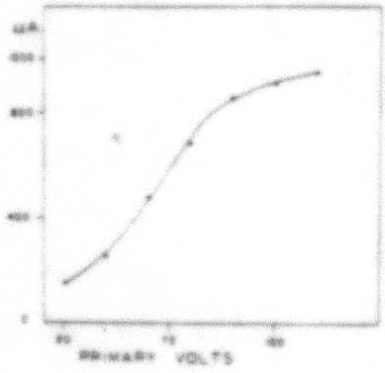


Fig.12--Variation of output current of generator with spray voltage.

The maximum available voltage from the generator has never been measured since the generating voltmeter measured the potential on the neutron generator and breakdown of insulation and leakage on this part of the apparatus set the upper limit. The highest potential obtained when connected to the neutron generator was 385 Kv. When disconnected, the high-voltage generator would go to much higher potentials since the voltage

would increase until sparking occured in air between the upper and lower housings, a distance of approximately four feet. According to Getting and Fiske, 800 to 850 Kv. is possible.

The leakage current at the voltages ordinarily used (200-275 Kv.) is quite small. Measurements at various times taken by subtracting the current to a corona point from the short-circuit current give values between 30 and 40 microamperes. Flashing occurs along the column, however, after the generator has been run for a matter of 100 hours without attention. Flashes and brush discharges along the outer surface appear to be due to the collection of soot and to a surface layer of moisture. Periodic swabbing with naptha followed by the application of a coating of ceresin dissolved in naptha eliminates this trouble. Flashing inside the column both along its length and between the column and belts ascribed to the presence of a black carbon-like deposit which gradually forms. Since the generator is rather thoroughly enclosed this could hardly be due to the ubiquitous coal soot but is believed to be from the material used to treat the belt to prevent surface leakage. This coating is readily removed by a cloth swab moistened with carbon tetrachloride--this being used instead of naptha as a precaution against a possible explosion from fumes trapped inside the generator.

The above cleaning procedures and a check of the belts, bearings, spray points, inspection for loose bolts,

etc., are carried out after each hundred hours of running time. Fresh drying agent is put in after each inspection. Cenco Dessigel S was substituted for the calcium chloride lumps originally used since this silica gel is much more effective and can be reclaimed by baking.

D. The accelerating tube. The initial focussing of the ion beam as it emerges from the probe is accomplished by means of a separate voltage supply consisting of a 30,000-volt R.M.S. transformer fed by the A.C. generator in the neutron generator housing and connected into a Greinacher voltage-doubling circuit. Two G.E. KR-1 half-wave rectifiers and two 0.2 mf., 30,000-volt condensers complete the elements of the focussing-voltage circuit.

The high-voltage transformer and a filament transformer with two 10-volt, 10-ampere secondaries insulated from each other and from ground are housed in a single oil tank. The secondary of the high-voltage transformer is in four sections and the connection between the two central coils was made available but not brought out of the case in the initial setup. A type 200 C variac (maximum current 7 amp.) provides voltage control. An overload relay is also used in the primary for protection and is connected to open the circuit ahead of the variac to prevent damaging it.

During the work with the Tuve-type ion source, the output of the voltage-doubling circuit was connected

directly to the second focussing electrode and across a bleeder resistance of about 75 megohms. Originally, the first focussing electrode was connected into different taps of this bleeder resistance. More stability was found, however, if this first electrode was connected directly to the midpoint of the condensers. This is shown in Fig.13 and Fig.14, the focussing circuit being shown only schematically in the second figure as the batteries E_2 and E_3 . This amounts to using the Greinacher circuit as two half-wave rectifier circuits in series.

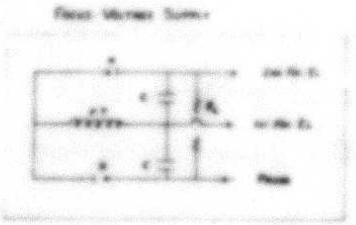


Fig.13--Diagram of focussing-voltage circuit.

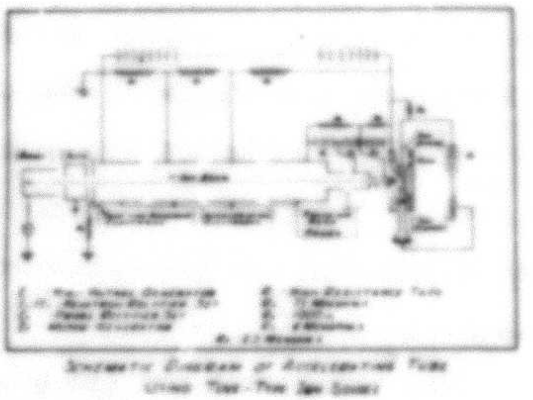


Fig.14--Schematic diagram of accelerating tube, using the Tuve-type ion source.

The above setup was used for most of the experimental work with the neutron generator but was modified when the Fowler-type ion source was installed to form a single half-wave unit whose output is connected directly across one focussing gap.

The original accelerating tube consisted of three sections of 6" pyrex tubing each 16" long. These sections were made from cylindrical jars by cracking off the bottoms of the jars and grinding the ends square. The jars were purchased instead of the tubing for reasons of economy. Being cast instead of blown, they were not quite uniform in diameter or wall thickness so it was necessary to fit each electrode support separately. The electrodes were made of thin 4" brass tubing and were fitted with 1/4" rings at the ends to minimize sparking across the gaps. The spacing of the gaps was not critical, values between 3/4" and 1½" being suitable. Each electrode was supported by a sleeve which formed a part of the assembly at the joints of the glass envelope. Electrode gaps could be adjusted by sliding the electrode in the sleeve but there was no provision for alignment, this being dependent on the alignment of the glass sections themselves.

The joints between the glass sections and the electrode supports were sealed with picein wax. The procedure in assembling the tube was to place the base of the tube (grounded-end with pumping lead) on the floor and level it with shims. The glass sections and the electrodes were then waxed on in the proper order, care being taken to keep the hot wax from flowing down the inner glass walls since bombardment of the wax causes it to give off gas. When the tube had been assembled and the wax hardened, the

unit was carefully put in place. Slings made from cotton rope boiled in paraffin were used to support the central sections of the tube and prevent sagging.

When the Fowler-type ion source was installed, several changes were made in the accelerating tube. The number of sections was increased from three to four and the 4" electrodes were replaced by 2½" electrodes. This last change was made to conform to the tube used by Fowler and was thought necessary to increase the focussing action which varies approximately inversely as the tube diameter. This change was probably a mistake since the chance of stray ions striking the walls of the tube and releasing secondary electrons is much greater and the aberrations due to small errors in alignment are larger. Much more difficulty was experienced in obtaining large ion beams with this new tube in spite of the provision for transverse adjustment of the electrodes for improved alignment.

The general problem of focussing ion beams can be calculated in advance if certain approximations and restrictions are assumed. These are:

1. All ions have same initial velocity.
2. Only ions travelling nearly parallel and close to the axis of the tube are considered. (Paraxial geometry).
3. Mutual repulsion of the ions is disregarded.

4. Aberrations and other second order effects are disregarded.

Then simplifying generalities will follow:

1. All ions are focussed in the same manner independently of their charge-to-mass ratio.
2. A change in the scale of the apparatus does not change its focussing properties if the relative dimensions are unchanged.
3. The relative magnitude of the potential differences being constant, the focussing is independent of their absolute magnitudes.

These simplifications make it possible to apply the rather extensive work on electron optics to positive ion optics. The discussions such as those in Maloff and Epstein's book: "Electron Optics in Television" then can be used directly. Since all the electrostatic lenses used in the present work consist of coaxial cylinders of equal diameters, the more specialized results of Kirkpatrick and Becherley (K-2) and Hansen and Webster (H-3), which deal with this case, are of more immediate value. These two papers combine the theory of focussing with an experimental determination of the fields between two equal cylinders to give the following lens formula:

$$\frac{1}{p}\left(1 + \frac{aV}{V+1}\right) + \frac{1}{q}\left(1 - \frac{aV}{V+1}\right) = \left(a\,\frac{V+1}{V+2}\right)^2 \frac{1}{R(.69+.50r^2)}$$

where p is the object distance, q the image distance,

$v = (V_2 - V_1)/500$ where V_2 and V_1 are the potentials of the two electrodes in kilovolts above the ion source, $a = (V_2 - V_1)/(V_2 + V_1)$, R is the radius of the cylinders and r equals twice the spacing divided by the radius, all dimensions being in centimeters.

On the basis of this equation, one can calculate the focussing action of any system of lenses and can predict the effect of various modifications--subject to the restrictions given above.

Unfortunately, the ion beams actually obtained by any ion source do not completely satisfy the limitations given. Many of the ions are not formed in the arc but in the capillary of the probe and have a reduced energy. The ions emerging from the probe suffer from mutual repulsion and therefore tend to diverge badly.

After experimenting with a wide variety of lens combinations it became apparent that calculations of the lens constants were valuable in finding the approximate conditions for focussing, but that wide variations from these ideal conditions must be expected for intense beams. In other words, there is rarely any difficulty in obtaining a moderately focussed beam approximately one centimeter in diameter if the total current does not exceed 5 to 10 microamperes but the conditions for focussing a similar beam of 200 to 300 microamperes may be quite different.

In order to overcome the initial divergence, the first focussing gap was placed at the end of the probe and the

second gap about 3" from this. The arrangement is shown in Fig. 14. These cylinders were 3/4" and 1½" in diameter, respectively. The beam emerging from these two lenses is now quite well defined and has an energy of some 40 Kv. so the subsequent lenses in the accelerating tube have a lesser effect and need not be adjusted as carefully.

The above setup was used with the Tuve-type source and yielded beams as high as 250 microamperes, measured after passing through defining slits ½" in diameter at the grounded end of the tube, some 50" from the ion source.

For such currents, voltage distribution between the three accelerating electrodes could not be accomplished by means of corona points. This was first attempted but was abandoned when repeated experiments showed that the setup was unstable. While the potential distribution did not seem to be particularly critical, it was necessary to maintain a bleeder current approximately equal to the beam current in order to prevent stray ions from charging up one electrode to the point of flashover. When the corona points were substituted by high-resistance tapes, this trouble disappeared.

The high-resistance tapes were constructed by ruling a line of India ink along a ribbon of ordinary drawing paper formed by gluing ½" strips end-to-end. The inked line was about 1/8" wide and was usually applied in a double coat to insure continuity. Each tape was about 6' long and was fitted with a copper contact on each end

which gripped the end of the paper. The resistance of each tape was 200 to 300 megohms. One tape was used for each section of the tube and was wound on the glass in a helix. It served the additional function of helping to remove the surface charges which tended to accumulate on the glass. The tapes were not entirely permanent and would occasionally develop high-resistances spots which caused sparking. Repairs of such spots was a simple matter, however, and it was felt that these tapes furnished a quite satisfactory solution to the problem of voltage distribution.

The fact that the gaps between the accelerating electrodes exposed the ion beam to the field from any charges collecting on the glass envelop caused some concern. Deflection and defocussing of the beam from such effects was evident particularly in the gap nearest the grounded end. To correct this, a shield of 5" tubing mounted on a sleeve to fit the electrode was placed over this gap so the ion beam could not "see" the glass. This proved effective. Another such shield was also placed on the next gap but this seemed to have no effect so was not used later.

Since the ions emerging from the probe are not monochromatic, it is not possible to satisfy the focussing conditions for all the ions. The central beam is consequently surrounded by a more diffuse but still considerable cloud of unfocussed ions which can strike the elec-

trodes and disturb the potential distribution by producing secondaries. These ions, also, do not constitute a useful load and are better removed from the beam. To accomplish this, a diaphragm which is not shown in the sketch of Fig.14 was placed in the accelerating tube between the second focussing gap and the first accelerating gap. The diaphragm had a 3/4" hole and was sectioned to offer a small resistance to gas flow. This served to cut down the load on the high-voltage generator but did not decrease the intensity of the focussed beam appreciably.

Some scattered beam still struck the end of the accelerating tube and produced secondary electrons. These could drift back up the tube into the accelerating field and then travel up the tube, constituting a useless load. To prevent this, an electron trap was constructed by insulating the end plate and connecting it to ground through the rubber water tubing used to cool the plate, this having an effective resistance of about 1/2 megohm. Collection of positive ions would then raise the potential of the plate to about 100 volts above ground. Any electrons released by the stray beam would then be attracted back to the plate since the electrode and assembly between the plate and the first accelerating gap were grounded. This was very effective and helped increase the beam intensity.

As mentioned before, this final arrangement yielded currents of 200-250 mi[illegible]s to the target at 200 to 250 kilovolts. Most of the experimental work was done

with this arrangement. When the new ion source was installed, the smaller electrodes mentioned above were put in and the high-resistance tapes were replaced by a resistance stack consisting of 12 200-megohm, 50-kilovolt resistors in series. Leads from this resistor stack were brought to the various electrodes. This arrangement is the one pictured in Fig. 1. Since this last arrangement was recently installed and not thoroughly tested, and since further modifications to be made when the outfit is moved to the new physics laboratory, it has not seemed worthwhile to discuss this new setup in detail.

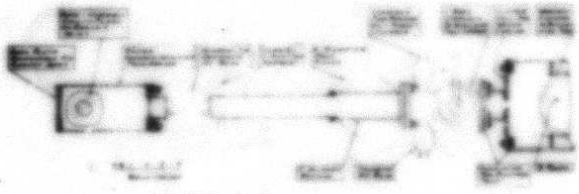


Fig.15--Top view of magnetic analysis and target assemblies of neutron generator.

E. Target and magnetic analysis. A plan view of the target assembly is given in Fig. 15. The beam passes through the large stopcock and through defining apertures into the target chamber where it strikes on a copper foil. This foil is soldered to a circular loop of ¼" copper tubing which extends into a nickel-silver Dewar flask above it. The flask contains liquid air which circulates in the copper tubing and keeps the foil cold. To activate

the target, one closes the large stopcock to isolate the target chamber and then opens the stopcock communicating with a small glass bulb containing a little heavy water. Enough vapor enters the target chamber to coat the target in about 5 seconds. About 10 seconds more should be allowed to permit condensation of all the water vapor before reopening the main stopcock. The remaining stopcock permits one to open the target chamber to the atmosphere or to connect it to the forepump so that work can be done on the target chamber without disturbing the vacuum in the rest of the system.

The target chamber is mounted on a frame which pivots about the center of the polepieces of the magnet. Free rotation is provided by a sylphon bellows. The beam can be observed by means of a small glass window waxed into the tube near the target chamber. Each section of the target assembly is insulated electrically from the other so the current to each can be measured. The insulation is afforded through gasket joints with the clamping screws fitted into bakelite bushings. The entire section containing the observation window can be removed, if desired, and the target chamber mounted directly behind the stopcocks if no magnetic analysis is to be used.

The magnetic field for the analysis is provided by a rather bulky electromagnet which happened to be available in the laboratory. It is equipped with 4" pole pieces

with a 2½" air gap. Fluxmeter readings show a moderately uniform field inside the polepieces of 2500 oersteds with a magnet current of 5 amperes. There is considerable fringing, as might be expected, but this is not of importance since the principal purpose is simply to separate the protonic ions from the other ions of the beam. This is easily done with a 5-ampere magnet current. The shifting of the various spots can be observed through the window of the tube and the target chamber swung to permit the desired spot to enter. A 0 - 200 microammeter connected to the target chamber measures the target current and a 0 - 1.0 ma. meter connected to the preceding section measures the residue of the beam so that a constant check on the total beam and the protonic beam can be maintained.

The analyzed beam was used in most cases because it was nearly as effective as the total beam and cut down on both the evaporation of the heavy ice target and the consumption of liquid air.

The following table compares the rate of decay of the ice target with resolved and unresolved beams. The activities are in arbitrary units measured by the rate of drift of a Lauritsen electroscope equipped with a boron-lined cap. The unresolved beam had an intensity of 200 microamperes and the resolved beam 37-40 microamperes. The voltage is the same in both cases: 250 KV. The time is the time in minutes after activation of target and the

activity is reduced to percentage of initial activity.

Time	1	2	4	7	15	17	26	34	40	51
Activity										
Resolved	100	-	100	100	-	87	87	84	84	63
Unresolved	100	70	52	48	0					

With the resolved beam, the activity is still above 50% of the initial activity after nearly an hour while the maximum life under the greater heating of the unresolved beam is less than 15 minutes. The decay is much less pronounced with a somewhat lower current, tests at 150 microamperes showing more than 60% of initial activity after 12 minutes. The gain is still considerable, however, since the analysis of the resolved beam discussed above showed only 17% protonic ions, 75% charged molecules and the rest indeterminate. This means that a total beam of about 250 microamperes would be necessary to obtain the same activity as the 40 microamperes of resolved ions. The liquid air consumption varies, of course, as the heat dissipated at the target. With the resolved beam it is only .4 liters per hour but is more than a liter per hour with the unresolved beam.

F. Pumping system. Two four-inch metal diffusion pumps in series, backed by a megavac mechanical pump are used to exhaust the accelerating tube. In the earlier work, the pumping lead was directly below the grounded end of the accelerating tube with no provision for isolating the tube from the pumps. Later a gate valve was added to the system so that the tube could be opened and worked on, then roughed

out by the fore pump without disturbing the vacuum in the diffusion pumps. The gate valve is of the type used on several of the vacuum systems in the laboratory, consisting of a gasket seal forced against the end of the pumping lead by a screw driven through a sylphon joint. When open, it offers small impedance to the flow of gas, but forms a vacuum-tight joint when closed under the combined pressure of the screw and external atmospheric pressure.

The speed of the pumping system was measured by the mercury pellet method* and yielded a speed (at the pumps) of 105 liters/sec at 1×10^{-4} mm., and 95 liters/sec at 4×10^{-5} mm. These were obtained with a 7/16" gap in the high-vacuum pump and a 1/4" gap in the roughing pump. The theoretical pumping speed of an aperture communicating with a perfect vacuum is 11.7 liters per second per square centimeter. The annular area of the nozzle of the high-vacuum pump is approximately 25 cm^2 so the theoretical limiting speed is 290 liters/sec. The efficiency is thus about 35%. Under best conditions, an oil pump can reach an efficiency of 50% to 60%. The speed actually attained seemed adequate, however, and was the maximum obtainable without drastic changes in the pump design. With the ion source in operation, a vacuum of 4 to 5×10^{-4} mm. could be maintained in the accelerating tube. With the gas flow shut

* The details of this method are given in Strong's "Procedures in Experimental Physics".

off, an ultimate vacuum of 5×10^{-6} mm. could be attained.

The pressure in the pumping lead between the pumps and accelerating tube is measured by an ionization gage operating at 3 ma. emission. Owing the presence of oil vapor and occasional operation at high pressures, some trouble was experienced with electrical leakage between leads on the surface of the glass press so the gage was constructed in a ground joint for easy access. The leakage seems to be due to a thin layer of tungsten and this is removed by washing the gage in an NaOH solution. Such a treatment cures the leakage for several weeks before a new coating forms.

G. Generating voltmeter. A Kirkpatrick-type generating voltmeter is used to measure the accelerating voltage. The photograph of Fig. 16 shows the general plan of construction. The rotor is made of two semi-cylindric segments of aluminum foil wound between layers of insulating paper. Leads are brought out to a commutator. The holder for the carbon brushes which are connected to the galvanometer is rotatable to permit setting for the largest deflection. The rotor is driven at 1800 R.P.M. by a synchronous motor.

The galvanometer is of the high-sensitivity wall-mounting type with a gold suspension and is critically damped. It is hung on a damped spring suspension to cut down extraneous vibrations. The light source is a 4.5-volt straight-filament lamp operated from a step-down

transformer.

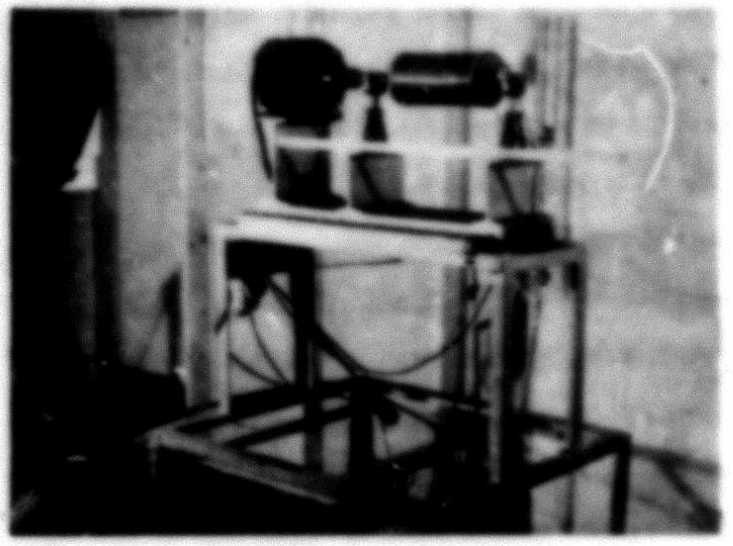


Fig.16--Generating voltmeter. The size of the unit may be estimated from the meter stick below the rotor. A portion of the neutron generator housing can be seen in the upper left corner.

The scale is curved with a radius of curvature equal to the galvanometer-to-scale distance. The entire unit was originally designed to be portable, which accounts for the construction used. The channels carrying the motor and rotor are supported on rubber mountings to reduce transmission of vibration to the galvanometer.

The generating voltmeter showed erratic fluctuations when first used which could not be correlated with corresponding voltage changes. The source of these fluctuations was finally traced down to thermal e.m.f.'s in the galvanometer circuit which had a free path during the instant the commutator was short-circuited

by the brushes. This was remedied by rebuilding the commutator with an insulated segment on which one brush rode while the other was changing contacts so that no short-circuiting was possible. When this was done, no further difficulty was found.

The generating voltmeter was calibrated by spark-gap measurements, using 12.5 cm. diameter spheres and the revised A.I.E.E. standards. Points were taken approximately every 40 KV. in the range between 80 and 180 KV. and gave a straight line, except for a slight bending at the lower end of the curve. A check of galvanometer deflection against current showed that this was a reproducible non-linearity in the meter itself. Since the calibration covered this non-linear portion and no experiments were anticipated which required an extremely accurate measurement of voltage, this non-linearity was tolerated. An accuracy of 2% is possible, even with these conditions. The extrapolation to higher voltages leads to some uncertainty but a check of the galvanometer sensitivity showed no changes in this region so a linear extrapolation is assumed.

<u>H. Measurements of neutron production.</u> Since the rate of neutron production depends upon the condition of the heavy ice target as well as the current and voltage, a monitoring device of some sort was needed in all the experiments. This is provided by a Lauritsen electroscope

with a boron-lined can. The coating is of amorphous boron mixed with a little Duco cement as a binder and forms an almost opaque coating of a thickness designed to equal the range of the boron-alphas. The electroscope is sensitive to all ionizing radiation and so has a background rate of drift when the neutron generator is running which is principally due to x-rays from the secondary electrons travelling up the tube and from gamma rays produced by fast neutrons. A box of 1/8"lead was made to house the electroscope and this greatly reduces this background. Since the cross-section of boron for neutrons follows the 1/V law, the electroscope is most sensitive to slow neutrons and this is utilized in checking the net deflection, since a cadmium shield cuts the rate of drift by a factor of three, if paraffin was used around the target.

This electroscope is used as a check on target decay, as already mentioned, and serves as a monitor in the neutron diffraction experiments.

<u>I. Detecting apparatus.</u> A Geiger counter setup utilizing a Neher-Harper circuit and a thyratron scale-of-eight circuit was constructed to measure the beta-radioactivity induced by neutrons. Since these circuits are well-known and in general use, no detailed description will be given here.

For the neutron diffraction experiment, an ionization

chamber filled with boron trifluoride gas was used with a linear amplifier of the Dunning type. It will be necessary to describe the linear amplifier in some detail in connection with the work on uranium fission, so a discussion of the circuit will be deferred until later. The ionization chamber is shown in Fig.17. Its construction

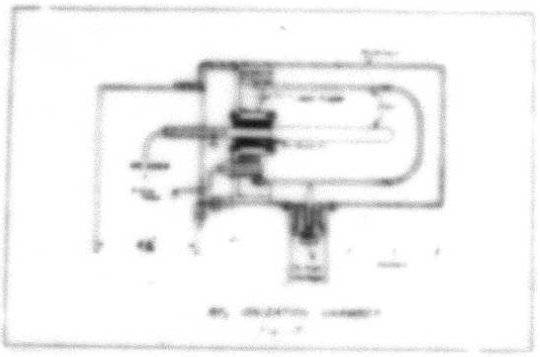


Fig. 17--Sectional view of boron-trifluoride ionization chamber.

is obvious from the sketch. After the chamber had been assembled, the joints were coated with hot cerosin and it was tested for vacuum leaks. It was then filled to atmospheric pressure with BF_3 and the filling tube sealed. The chamber works well with about 800 volts on the high-voltage electrode. The central electrode is connected directly to the grid of the first tube of the linear amplifier. The output of the linear amplifier is fed into the same thyratron scaling counter which is used with the geiger apparatus. Due to the noise and mechanical vibration of the supporting table when the high-voltage

generator is running, it is necessary to mount the ionization chamber and first stage of the amplifier in a cradle supported by taped springs to eliminate false counts. With this precaution the background amounts to only about 8 counts per minute with the generator running but no beam on, while 480 counts per minute are registered with the beam on and 140 counts per minute with a cadmium shield interposed.

III. Investigation of Indium

A. Discussion. Goldhaber, Hill and Szilard (G-2) have investigated the activities induced in indium by neutrons from a radon-beryllium source and found that the 4.1-hour period is produced more strongly than the 51-minute period. They did not find the 4.1-hour period when they used the photoneutrons from a strong radium-beryllium source although the 51-minute period was very strongly activated. The photoneutrons have an energy of somewhat less than 1 Mev. whereas the neutrons from the radon-alpha-beryllium source have a maximum energy of 13 Mev. The conclusion from this investigation is that the two activities could not be assigned to isomers of the same isotope since their excitation energies are so different. Since the 51-minute period had already been definitely assigned to In^{116}, formed by neutron capture, and indium has but two stable isotopes: 113 and 115, the 4.1-hour period must be assigned to In^{113} or a new mechanism other

than neutron capture must be postulated. In^{113} has a relative abundance of only 5% so it was ruled out as requiring too large a cross-section to give the activities observed. Finally, the experiment was repeated with the 2.8 Mev. neutrons from a heavy-ice target bombarded by deuterons and a strong 4.1-hour activity observed. Since the available energy from these neutrons is much less than the binding energy of a neutron in an indium isotope, processes involving neutron loss were eliminated. A new type of process was therefore proposed: formation of a metastable state of In^{115} which could revert to a stable nucleus by beta-disintegration or by gamma-emission and internal conversion. This postulate was confirmed by further experimental work which need not be detailed here.

It was thought to be of interest to repeat the experiment of bombarding indium with D-D neutrons to confirm these results and investigate further possibilities. Accordingly, a series of such bombardments were made under various conditions as detailed below.

<u>B. Procedure.</u> The target chamber was surrounded by blocks of paraffin during all this work in order to keep the intensity of fast neutrons below a value which might be harmful to the workers. This meant that there was a copious supply of slow neutrons in all the bombardments.

The first run was made by placing an indium foil on the back of the target itself without any shielding. A

50-minute bombardment with an unresolved beam of 175 microamperes at 250 KV gave a strong initial activity of 2000 counts/minute which decayed with the 54-minute period, showing no longer-lived activity. It was suspected that the 4.1-hour activity might be masked by the much stronger activity of the 54-minute period. This latter is known to be water sensitive and to have a resonance in the region of thermal energies. To cut down its intensity, cadmium was placed around the sample in the next bombardment. This sample then showed both activities, the 4.1-hour activity having about 1/6 the intensity of the 54-minute.

During this last bombardment, short bombardments of another sample of indium were made to detect the 13-second activity which is assigned to In^{116}. The procedure consisted of making bombardments of about 30 seconds and then rushing the sample to a counter and taking readings every 5 seconds until the activity disappeared. Several runs gave an average period of 15 seconds, which agreed with the accepted value of 13 seconds within the experimental error.

A number of runs were made with two indium samples placed behind the target with a lead absorber between them to determine whether or not the 4.1-hour activity might be due to gamma-rays from the D-D reaction. No significant difference which could not be accounted for by the geometry of the bombardment was found, so it was

concluded that the gamma-rays probably have no effect.

Since the cadmium shielding still gave a 4.1-hour activity which was much weaker than the 54-minute activity, it was assumed that the cadmium was not effective in eliminating the resonance neutrons to which the 54-minute activity is most sensitive. This was based on resonance energy measurements listed in Bethe's article (B-3) (page 137) where the resonance energy for the 54-minute period is estimated at 2.6 volts and was confirmed recently by the work of Baker and Bacher (B-1) who made transmission measurements with monochromatic neutrons and found a value of 1.0 volts. Cadmium strongly absorbed neutrons of .3 volts energy or less but is not effective at higher energies.

An experiment to check this argument was made as follows: Three samples were bombarded simultaneously, the front sample being next to the target, the middle sample sandwiched between two indium absorbers of about 1.5 mm. thickness each, and the back sample placed behind the sandwich. The whole assembly was put in a cadmium box. Two such bombardments were made of four hours each, using a resolved beam of 30 microamperes of deuterons at 250 KV. The samples were then placed in holders which permitted them to be removed from the counters and replaced in the same position. Counts were taken for some 14 hours after the bombardment.

The net number of counts per minute for each sample was plotted on semi-logarithmic paper and graphical analysis made of each curve to separate the two periods By extrapolation to the time when the bombardment ended, the initial number of counts per minute from each sample could be computed. From the known half-life of each period the ratio of the number of radioactive nuclei of each kind was determined. Since the samples were not of exactly the same size, the counts were reduced to terms of counts per minute per square centimeter. A further correction was made for the fact that the samples were not at the same distance from the source of the neutrons.

C. Results. The results are given in the following table. Column I gives the net counts per minute of each period at the end of bombardment. Column II gives the ratio of number of active nuclei of each period. Column III corrects the results of the preceding column for the distance from the target; and Column IV gives the number of counts per minute per square centimeter of the 4.1 hour period corrected for the distance from the target.

	I		II	III	IV
	54 min.	4.1 hr.	4.1 hr. / 54 min.	4.1 hr. / 54. min.	4.1 hr.
Front	866	123	.68	.68	123
Middle	364	112	1.4	1.6	125
Back	880	102	.53	.65	124

From this data we can draw certain conclusions:

(1). From the fact that the number of counts per minute of the 4.1-hour period is the same for all three samples when the distance from the target is considered (Col. IV), there must be negligible absorption of the neutrons which produce this reaction.

(2). The back sample was much thicker than the other two but yet gave the same number of counts per minute. This means that even the thinner samples were sufficiently thick to absorb the beta-rays coming from the back of a sample.

(3). The intensity of the 54 minute period (Col. I) is stronger in the back sample than in the front one. Since this period is known to be caused by slow neutrons, most of its activation comes not from the direct beam of neutrons, but from those which have left the target chamber, collided with protons in the paraffin block surrounding it and then diffused back into the target chamber. Thus the target chamber is filled rather uniformly with slow neutrons which excite the 54-minute but not the 4.1-hour period. The increased activity of the back sample comes from the fact that it was nearer the wall of the chamber and hence nearer the source of the <u>slow</u> neutrons than the front sample.

(4). The great decrease in the intensity of the 54-minute period in the middle sample as compared with

either the front or the back sample indicates that the indium disks used as absorbers were quite efficient in removing the slow neutrons. The absorption cross-section can be calculated from the data above.

The absorption law is given by $N = N_0 e^{-nat}$

where N = number of neutrons penetrating to a thickness = t

N_0 = number of neutrons incident on the absorber

n = number of absorbing atoms per unit volume

and

a = effective absorption cross-section per atom.

The data gives:

$N = 870$ $\qquad$ $n = 3.85 \times 10^{22}$

$N^0 = 360$ $\qquad$ $t = 0.18$ cm.

From which $a = 1300 \times 10^{-25}$ cm^2. The value quoted by Bethe (B-2) (page 151) is 1500×10^{-25} cm^2, which is quite good agreement since a limited supply of indium did not permit the construction of sufficiently large absorbing disks to be certain that the edges of the sample were not exposed.

IV. Neutron Diffraction

A. Method of focussing. In March, 1936, Dr. K. Lark-Horovitz, in a proposal for a research grant to assist this work, discussed the problem of neutron diffraction. It was pointed out that due to the low intensity in using a parallel beam, focussing methods would have to be

utilized. Three different methods have been suggested: (1). Crystals of fatty acids deposited on a properly bent glass surface; (2) a hollow cylinder of diffracting material so that the neutrons would be focussed onto the axis, and (3) a Johannson-type of spectrometer with a crystal cut and bent so as to achieve proper focussing.

The problem is to bombard a crystal at a known angle with neutrons of low energy and observe the intensity of the diffracted neutron beam as a function of the angle. Ideally, if monochromatic neutrons are used, very sharp maxima of intensity should be observed for the angles at which the Bragg equation is satisfied. Thermal neutrons are to be used for this purpose since their deBroglie wavelength, calculated by $E = 1/2\ mV^2 = 3/2\ kT$, is

$$\lambda = h/\ (3mkT)^{\frac{1}{2}} = 1.5\ \mathring{A} \quad \text{for } T = 300^{\circ}.$$

As already seen, the thermal distribution is far from mono-chromatic, but the above value can be taken as the most probable wavelength of the neutrons. Due to the rather broad distribution of wavelengths about this value, it can be expected that: (1) only a rather broad maximum can be expected at the Bragg angle calculated for this value, and (2) an overlapping of different orders of reflection might possibly smear out the entire diffraction pattern.

Since neutrons cannot be focussed and the intensity of a well-collimated beam would be rather small, the

Johannson (J-2) method of diffraction is used. This method consists of allowing radiation from a point or line source to strike on a crystal which has been both bent and ground. The arrangement is indicated in Fig. 18.

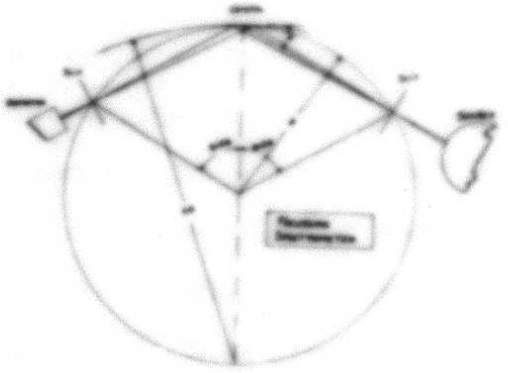


Fig.18--Focussing with a Johannson-type spectrometer.

The source, which may be a slit illuminated by a broad source, is located on the focal circle. The diverging rays from this source strike the crystal and are focussed to intersect at a corresponding point on the circle. The front face of the crystal is tangent to the focal circle. The crystal is bent to a radius equal to 2r and then ground to a radius equal to r. The radial angle ϕ and the Bragg angle θ are related by $\phi = 2\theta$ so the Bragg angle can be determined directly from readings on a graduated circle concentric with the focal circle.

A crystal suitable for such work with neutrons must: (1) Have a rather small lattice constant to permit a

usable Bragg angle; (2) be sufficiently elastic to permit the bending operation; (3) be fairly perfect single crystal; (4) not absorb neutrons strongly; (5) preferrably be made of elements having a single isotope, and (6) be made of elements having a small nuclear spin to give strong scattering.

These restrictions severely limit the number of substances available. Mica and gypsum are very easily bent but have large lattice constants. Rock salt has a suitable lattice but the chlorine absorbs neutrons strongly. Quartz (SiO_2) was found to come nearest to meeting all the specifications. Johannson used this in his original work on X-rays, giving assurance that the elastic properties are adequate. Its lattice constant (prism face) is 4.2449 angstroms, for which the neutron Bragg angle is about 10°. Quartz is a highly perfect crystal and neither silicon nor oxygen have large cross-sections for thermal neutrons. Oxygen is essentially all of mass 16 and silicon is 90% mass 28 so the isotope effect should not be large. The nuclear spin of O^{16} is zero and that of Si^{28} is probably zero.

Three quartz crystals, each 18 x 30 mm. and 0.5 mm. thick, were purchased from the same firm which furnished the original crystals for Johannson. These crystals have the front face ground to a radius of curvature of 50 cm. and are therefore designed to be bent to this radius and used on a 25 cm. focal circle.

Plans were drawn up for the spectrometer, following the original design of Johannson. As originally planned, the spectrometer was arranged to be used in vacuum, so that it could be used later for x-ray work in the longer wavelength region. For the neutron experiments, the vacuum chamber was unnecessary, due to the small absorption and scattering of neutrons by air, and was an actual disadvantage since shielding was complicated by the presence of steel walls. Accordingly, the crystal holder was removed and placed on another mounting.

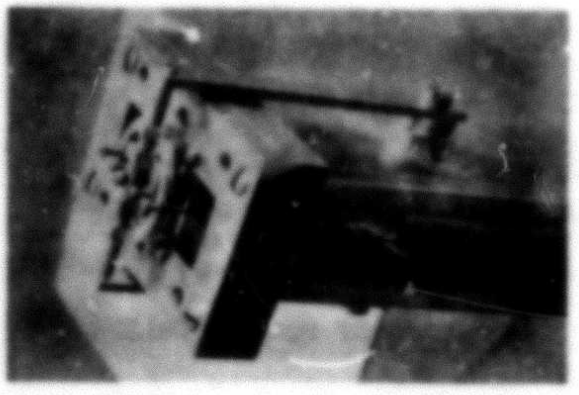


Fig.19--Crystal holder for spectrometer.

The general construction of the crystal holder can be seen in the photograph of Fig.19. Two aluminum bars form a rigid arm which supports the steel crystal holder and bending mechanism. The crystal is clamped against the lips of the holder by two strips of spring steel which are bent by the action of the screws threaded in the concentric rihgs. These rings are pivoted to help equalize the pressure. The spring steel strips help to

distribute the pressure over the length of the crystal. The lips of the holder have a radius of curvature of 25cm. and form an opening 10 mm. wide through which the beam can strike the crystal. The effective area of the crystal is thus 3 cm.^{2}. A strip of cadmium is placed immediately behind the crystal to absorb neutrons which otherwise might be scattered from parts of the bending mechanism.

The bending mechanism appears to be very successful. The original quartz crystal is still intact after being removed and replaced several times.

In order to test the effectiveness of this method of focussing, the spectrometer was taken to the x-ray laboratory and set up at a tube with a copper target. The copper K-alpha line has a wavelenth of 1.54 angstroms, which is very nearly that of thermal neutrons, so was particularly suitable for this work.

With the assistance of Dr. E.P.Miller, several pictures of the copper K-alpha doublet were taken by lining up the spectrometer with a fluorescent screen and placing the film on the focal circle at the position of the observed diffracted image. Fig.20 shows a contact print from a pair of pictures taken in the fourth-order with a .005" slit. The exposure time was 5 minutes and the crystal slowly moved back and forth over the proper range during the exposure. This last is necessary with a well-defined source since the focussing properties are

very critical and it was not even found possible to obtain both components of the doublet with a single setting and stationary crystal. The pictures indicate the rather sharp focussing which can be obtained with this method.

Fig.20--Copper K-alpha doublet in fourth order with quartz crystal.

Some work was also done with rock salt crystals. Thin sections were cleaved from a larger crystal and placed in a clamp turned to a 50 cm. radius of curvature. This was then placed under water and slowly tightened. The mortality in this process was about 75% but several good crystals were obtained. The rock salt bends plastically so retains its shape. Pictures were also taken with these crystals. They showed as good resolution as the quartz, but exhibited a peculiar step-like structure along the length of the lines which was ascribed to the fact that the crystal, in the bending process, breaks up into a number of smaller crystals which are slightly

tilted. The rock salt was not used in the neutron experiments because, as already mentioned, chlorine shows strong absorption for thermal neutrons.

B. Measurements with boron detector. The BF_3 chamber already described was used as a detector in the measurements made with the neutron generator. The neutron camera was constructed by mounting the crystal holder on a vertical axis and making cadmium slits and mounting them on separate arms to pivot on the focal circle. A graduated circle was mounted on the same axis. The source of the neutrons was a ball of paraffin which formed a 4" layer around the target chamber of the neutron generator.

Measurements were made by measuring the number of counts recorded from the BF_3 chamber for 80 divisions drift of the boron-cap Lauritsen electroscope, which was placed near the target and used as a monitor.

Serious difficulties were at once found in attempting to reduce the background counts due to scattered thermal neutrons and to faster neutrons which are not stopped by cadmium but can be registered by the ionization chamber. To make the shielding as complete as possible, a long mounting tube was put on the ionization chamber and the whole assembly coated with cadmium and then buried in a block of mixed borax and paraffin. Only the front of the chamber was left uncovered. The cadmium slits of the neutron camera were substituted by hollow cadmium wedges

filled with the mixed paraffin and borax. Blocks of this same mixture were cast and mounted up to intercept the randomly scattered neutrons. One-gallon cans filled with concentrated borax solution were used for the same purpose.

With all these precautions, the background count was reduced considerably but still amounted to 10% of the beam through the slits. This could be improved by inserting more absorbing material between the source and the first slit to leave only a narrow channel for the useful neutrons. This involved increasing the distance between source and slit and a corresponding decrease in intensity--which already was low.

Many attempts were made with various setups but none yielded any significant results. For the standard bombardment as measured by the electroscope monitor, typical counts are as follows: Direct beam:3200; shielding inserted: 7; crystal in place, slits set for expected Bragg angle (10°), crystal moved 0.5° about central position between runs: 7 to 10; neutron generator on but beam deflected from target: 2 in two minutes.

From the negative results thus obtained one can only conclude that the intensity of the diffracted beam, if it exists, is less than the background. While it seemed hopeless to continue the work with the present arrangement, this left the experiment in a most unsatisfactory state, since it was not possible to assign

a lower limit to the diffracted intensity.

C. Measurements with Dysprosium Detector. In an attempt to repeat the experiment in a different manner to achieve better results, possible improvements were considered. These are: (1) Higher incident neutron intensity to permit more effective shielding by thicker absorbers; (2) a more accurate monitoring system to decrease errors from intensity fluctuations, and (3) a new detector which is sensitive only to thermal neutrons.

By this time the Purdue cyclotron was in operation with deuterons and supplied a much more intense neutron source. It was therefore decided to abandon the neutron generator temporarily. The problem of monitoring would be solved if the measurements for all angles could be made simultaneously. Dysprosium, a rare earth, was suggested as a possible detector since it has a very large cross-section for thermal neutrons (700×10^{-24} cm^2) and its 2.5-hour period is not excited appreciably by faster neutrons.

A 100-milligram sample of Dy_2O_3 was ordered from the Fairmont Chemical Co. and work started on a new neutron camera. Figures 21 and 22 show a plan drawing and photograph, respectively of the completed camera. Slits are entirely eliminated since the focussing properties of the crystal are such that only radiation which starts from the proper position on the focal circle will be focussed.

Experiments on diffusion of slow neutrons in paraffin have shown that the mean-free-path of a thermal neutron is 3 mm. This means that any neutron emerging from a paraffin surface must come from a point within 3 mm. of that surface. If a block of paraffin is therefore milled to fit the focal circle, it serves as an extended neutron source. A cadmium shield exposes only a narrow strip of the paraffin face equal in width to the height of the crystal.

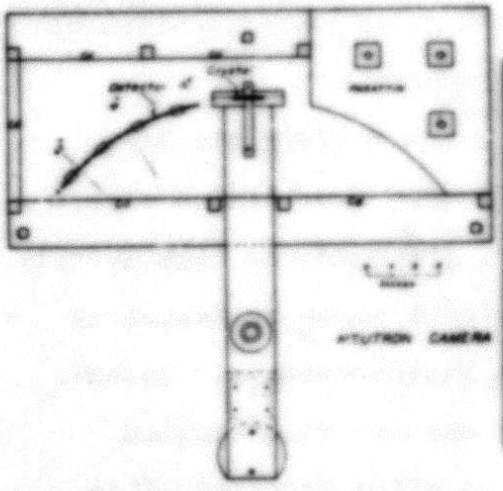


Fig.21--Plan drawing of neutron camera.

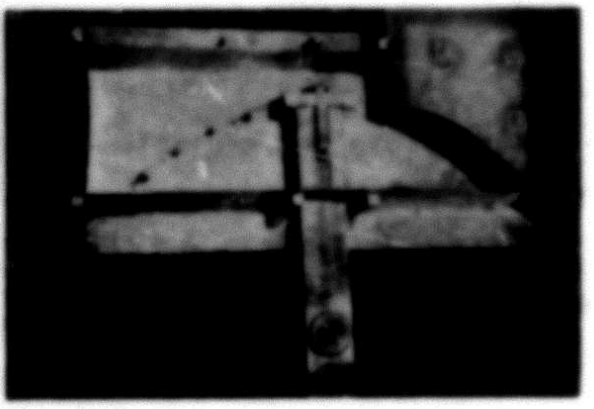


Fig.22--Top view of completed neutron camera with lid and some of the shielding removed.

However, this type of a source produces a widening of the image and, as a consequence, reduces seriously the definition of the spectrograph. We believe that part of the uncertainty in the results is due to this difficulty which will be removed in a new construction.

The continuous detector is made by mixing the Dy_2O_3

with a little rezoglaz cement as a binder and spreading it in a uniform layer along a strip of cadmium. The cadmium then can be bent and fitted into holders to lie along the focal circle. This method makes the measurements independent of fluctuations in neutrons intensity during bombardment. A somewhat higher background might be expected with this arrangement than with an arrangement in which the crystal is rocked and a slit moved to uncover only the part of the detector irradiated by the diffracted beam but the difficulties and uncertainties of this last arrangement also are greater.

The fact that the neutrons which satisfy the Brugg relationship for any given energy must come from a narrow region of the paraffin surface at first caused some anxiety, since both the distance and the solid angle subtended by the crystal are functions of the incident angle. Another factor also enters, which is the angular distribution of the neutrons emerging from a paraffin surface. This has been calculated by Bethe (B-2) (Page 133) who shows that the distribution is proportional to $(\cos \theta + 3 \cos^2 \theta)$ where θ is the angle with the normal. This factor, together with the changing solid angle subtended by the crystal as angle ϕ (Fig.18) is varied, fortunately compensates for the smaller distance from paraffin to crystal so that no more than a variation of a factor of two is to be expected in changing ϕ from 40° to 18°. Due to the focussing action of the crystal, no variation in

the diffracted beam due to changing crystal-to-detector distance is to be expected, although the diffuse scattering might be expected to decrease for large values of ϕ.

When the dysprosium arrived, it was tested for neutron activity and for sensitivity to fast neutrons. For this purpose, the sample was divided into two nearly equal parts and placed in .001" pliofilm envelopes. One sample was tightly enclosed in a cadmium sandwich and the other backed by cadmium but left open in front. These samples were placed side-by-side with 3½" of paraffin between them and the cyclotron target and bombarded for one hour. The open sample gave an initial activity of 600 counts per minute (on the scale-of-eight) and the shielded sample 30 counts per minute, indicating that the fast neutrons were responsible for only 5% of the total activity.

An interesting sidelight as to the possibility of using neutron bombardment for quantitative analysis might be worth mentioning. A second 100-milligram sample of Dy_2O_3 had been received, was mixed with rezogez and spread on a cadmium strip. It was then bombarded for the purpose of measuring the uniformity of the coating but gave practically no activity. Check boubardments of this sample together with the original samples showed that the new sample contained practically no dysprosium. Communications with the chemical company established that this new sample had come from a new batch which had apparently not

been sufficiently purified. The sample was returned. Owing to the difficulty of chemical methods of analysis in the rare earths, this suggests a field for nuclear physics. In this particular case, the instance was unfortunate, since it involved a delay of several weeks.

Another 40 mg. of dysprosium oxide from the original batch (all which was available) was purchased and a continuous sample of about 90 mg. was made, spread into a thin layer 1 x 20 cm. on a cadmium sheet. This was given a uniform bombardment in a paraffin sandwich and the activity of successive lengths measured by placing a lead sheet with a small aperture between the sample and the counter. The size of the aperture was chosen and the sample marked in such a manner that each exposed portion corresponded to a radial angle of 2.5° in the neutron camera. The counts were reduced to activity at zero time and reduced to unit activity. The result is shown as the solid curve in Fig.23.

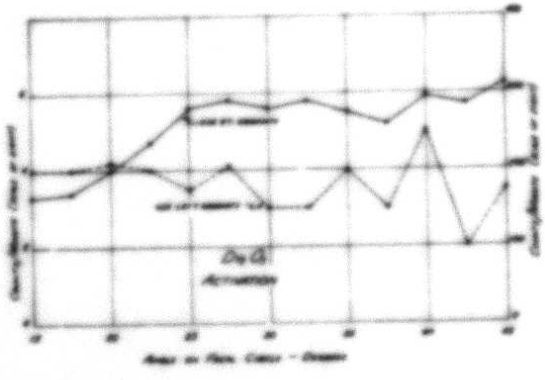


Fig.23--Activation of dysprosium sample. Solid curve is from uniform bombardment in paraffin sandwich. Dotted curve taken in

neutron camera.

Actual attempts to find the neutron diffraction were now made. The neutron camera was placed in front of the cyclotron target with the outer portion of the paraffin block in contact with the target chamber. The dysprosium sample was put in place and cadmium shields (not shown in diagram) placed to thoroughly block out the direct beam between the paraffin and the dysprosium. A small dysprosium sample on a scrap of cadmium was laid in a reproducible position on the floor of the camera. The cadmium cover was then put on and the bombardment started. Two bombardments of 2.5 hours each were made. The deuteron beam averaged about 1/2 microampere and had an energy of 8 Mev.

After bombardment, counts were taken on the continuous sample with the same setup used for its calibration. The activities were very weak and only of the order of twice the natural background of the counter. Under the same counting geometry, a section of the sample which gave 250 counts/min. in the direct beam outside the camera after a 1/2-hour bombardment, gave only 3 to 4 net counts/min. after 2½ hours bombardment in the camera. The small sample in the floor of the camera also had a much weaker activity yielding only 42 counts/min. in the camera against about 600 in the direct beam.

With such small activities, no definite conclusions

can be drawn. A sample curve from these measurements is shown in Fig. 23. The existence of a diffraction peak might be read into the variations if it were not for the weak activity which makes the statistical fluctuations very great and the fact that successive runs did not reproduce the peaks with the possible exception of the at 35° which would thus be regarded as a second-order reflection of 1.5 Å neutrons. This interpretation is difficult to reconcile with the absence of a first order peak in the neighborhood of 20°.

The experiments thus far must therefore leave the question of neutron diffraction unsettled. It is believed that the method used is essentially correct and that a greater neutron intensity and a larger dysprosium sample would succeed in giving definite information. The larger neutron intensity should be available when the new oscillator is installed in the cyclotron. Unfortunately, pure dysprosium oxide is both expensive and difficult to obtain. An additional 100 mg. have been obtained since these experiments were made and further work is being considered.

It has been suggested that the apparent failure of the focussing-crystal method is due to the broad distribution in energy of the neutrons together with the critical focussing conditions of the crystal. A crystal which retains the focussing properties but which has a

smaller "resolving power" might help this matter. If one could make a series of 15 daily runs with a suitable monitor in which all the dysprosium is concentrated in a small sample and placed at various positions on the focal circle the intensities could be greatly increased, also.

At the time this part of the work was concluded, a report by Thiessen (T-3) at the Washington meeting of the American Physical Society gave results of Bragg reflection experiments, using seven large single crystals of MgO, neutrons from the Columbia cyclotron and a boron detector. Heavy shielding was used, in spite of which the background was about equal to the scattered intensity. His results showed that the coherent scattering was from 60 to 80 percent of the total scattered beam and that a Maxwell distribution was observed. No further publication on these experiments has been made, to the author's knowledge.

There have also been a number of investigations, cf. (B-6) and (R-1), in which the difference in transmission of single and multiple crystals has indicated the necessity of coherent scattering but no direct attack was made on the problem.

If sufficient intensity is obtainable, the various methods of obtaining monochromatic neutrons already mentioned should remove the shielding difficulties and

permit unambiguous measurements of the Bragg reflection to be made. It is hoped that such measurements can be made in this laboratory later when higher intensity sources are available.

V. Uranium Fission

A. Statement of problem. In all the experimental work done on the problem of fission, no investigation of the effect of increased energy of neutrons on the mode of fission produced had been done by the spring of 1940. However, in a discussion of the results of Jentschke and Prankl with different neutron energies, Dr. K. Lark-Horovitz pointed out that the valley between the peaks observed in the energy distribution curve seems to increase with increasing neutron energy. This would indicate symmetrical fission and he suggested that, therefore, a systematic investigation of the fission as a function of the neutron energy should be carried out.

It had been shown that uranium fission occured both with fast and slow neutrons but there was no systematic investigation of the differences between the two processes. This investigation is of theoretical interest since the liquid-drop picture of the nucleus leads to the possibility of new modes of fission coming in as the neutron energy increased. Detailed calculations by Present and Knipp (P-1) (P-2) indicate that two modes of binary fission are possible,

one symmetrical and one unsymmetrical. The calculations were not able to determine which of the two should require the smaller activation energy. Besides the ordinary binary fissions, there is also the possibility of ternary fission. Later calculations by Present (P-3) indicated that such a process of division into three equal droplets is possible and should release about 20 Mev. more energy than binary fission. The activation energy is the same as for binary fission but the process is less probable for low neutron energies because of the less direct process involved.

By measuring the recoil energy of the fission particles in an ionization chamber and applying the law of conservation of momentum it is possible to decide between the different modes of fission produced. Measurements of recoil energies have already been made by Kanner and Barshall (K-1) using D-D neutrons and by Jentschke and Prankl (J-1) using slow neutrons from a Po-Be source, as already mentioned. Each found two main groups of particles with energies of approximately 64 and 96 Mev., respectively, but the height of the valley between the two peaks in the distribution curves appeared to increase with increasing energy of the neutrons. It was therefore thought that this might indicate the beginning of a symmetrical fission. If this is true, use of the high-energy neutrons from the Li-D reaction should show a much greater effect. It was therefore proposed to attempt this experiment.

In the meantime, Yasaki (Y-2) and Segre and Seaborg (S-2) have investigated the chemistry of fission products by fast neutrons. They found new fission fragments identified as isotopes of palladium, silver, cadmium and indium which were not proviously found with slow neutrons.

Also, the experiments of Dr. K. Lark-Horovitz and W. A. Miller on photographic plates indicate definitely not only asymmetrical tracks but also symmetrical tracks. It is therefore clear that one should find, from the energy distribution curve, the definite percentage and cross-section of symmetrical fission processes.

B. Experimental procedure. The experimental arrangement for measurement of the recoil energies consists of a special ionization chamber connected to a linear amplifier which feeds the pulses into a recording oscillograph through a single-stage current amplifier. A cathode ray oscillograph is also connected to the linear amplifier to give a continuous check on the operation of the equipment. Calibration of the pulses is obtained by use of an artificial pulse generator patterned after that of Kanner and Barshall (K-1).

The various units are seen in Fig.24. The linear amplifier and its power supplies are mounted on a rolling table. On the top of the table may be seen the three last stages of the amplifier with the cable leading to the first-stage and ionization chamber. Behind the

amplifier is the cathode-ray oscillograph. The front chassis on the middle shelf contains the power supply for

Fig.34--View of linear amplifier and recording oscillograph.

the amplifier. Back of this and to the left is the stabilized high-voltage supply for the ionization chamber shielded with copper mesh. In the far corner of the middle shelf is the chassis with the current amplifier. The bottom shelf holds the storage battery and charger for the filaments and a pair of 45-volt batteries which bias the regulating circuit of the power supply. The large box on the wooden table contains the recording oscillograph and the small steel cabinet on top houses the artificial-pulse generator.

The arrangement used is not as neat as a relay-rack mounting would be but is far more accessible. The power units are self-contained (except for one set of bias batteries) and are plugged into a bank of outlets controlled by a master switch. All leads connected with the

amplifier are carefully shielded.

The various units mentioned above will now be discussed in detail.

(1). Ionization chamber and linear amplifier. Since the full range of the fission fragments must lie within the ionization chamber, a special chamber with a large volume is required. The maximum range of the fragments has been variously measured as 1.8 to 2.4 cm. The ionization chamber was therefore designed to have the nearest wall greater than 3 cm. from the uranium layer. In order to permit the simultaneous measurement of both recoil particles, the grid electrode, which served as a support for the uranium layer, was placed in the center of the chamber. A cross-sectional view of the ionization chamber is shown in Fig.25.

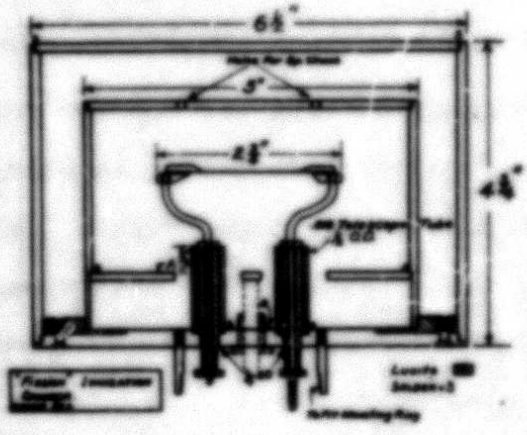


Fig.25--Section through ionization chamber.

The grid electrode is supported on brass rods which are insulated from ground by lucite bushings. The longer

of these rods is connected to the grid of the W.E. 259B used as the first amplifier tube. Grounded brass sleeves surround the lucite bushings and extend up through the clearance holes in the high-voltage electrode to act as guard rings. The high-voltage electrode completely encloses the central volume except for the clearance holes for the grid electrode supports. The lead-in for the high voltage is a brass rod, insulated by a phenolite bushing where it passes through the grounded wall of the chamber. It is shown in the drawing between the two grid electrode supports.

The high-voltage electrode is threaded into a lucite ring which is screwed onto the brass base plate. The entire chamber is shielded by a brass can which is threaded onto the rim of the base. Access to the chamber is gained by removing the shielding can and unscrewing the flat circular disk which forms the upper wall of the high-voltage electrode.

To minimize insulation troubles, the lucite ring was coated with hot ceresin wax after assembly. After some trouble with acoustic pickup had been experienced, hot ceresin was also used to fill the space between the lucite bushings and guard sleeves in the grid-electrode assembly. This eliminated the trouble.

The chamber was not originally designed to be evacuated but it was later found necessary to use pure argon

as the filling gas, so certain modifications not shown in the drawing were made. A rubber ring gasket was placed in the butt joint between the shielding can and the base to provide a vacuum-tight seal at that point. To eliminate the leaks in the base, the chamber was inverted and a layer of ceresin ¼" deep poured into the mounting tube. When this had hardened, a sharp tool was used to cut a circle around each of the grid-electrode supports in order to prevent electrical leakage between the high-voltage and the grid. The heads of the screws holding the large lucite ring were also coated with ceresin.

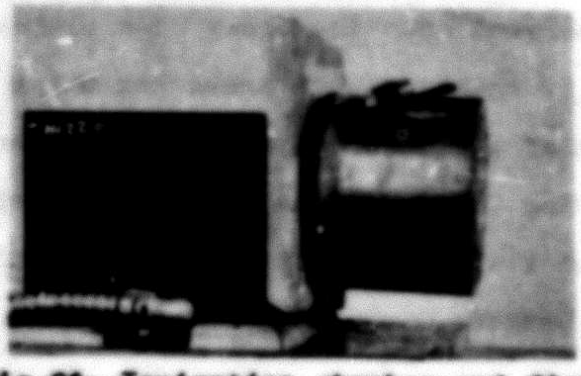


Fig.26--Ionization chamber and first stage of amplifier.

The ionization chamber is mounted on the side of the steel box which contains the first stage of the linear amplifier. The grid and high-voltage connections are accessible from the inside of this box. A photograph of the unit is shown in Fig.26. The slab of cast paraffin and borax is part of the fast-neutron shielding described later.

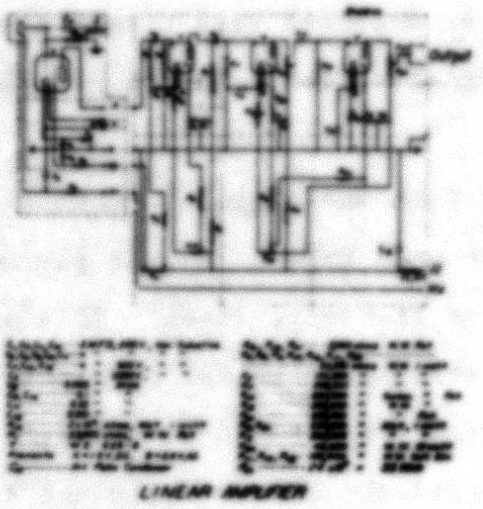


Fig.27--Linear amplifier circuit.

The linear amplifier is of the type developed by Dunning (D-2) and follows his original circuit with only minor changes. The circuit diagram is shown in Fig.27. The portion of the circuit at the left, shown in a separate shield, is the first stage which is housed in the separate steel box carrying the ionization chamber and connected to the remainder of the amplifier by a 22-foot cable of ½" flexible conduit. This permits the ionization chamber to be placed in position near the target of the cyclotron while leaving the main amplifier in the adjacent room beyond the water tanks so adjustments and observations can be made during the runs. The filament, screen grid, plate and high-voltage leads are individually shielded by braided copper sheathing and the group of wires finally enclosed in a larger braided shield before being pulled through the conduit. As a result of this careful shielding

no trouble was experienced with pickup even in the strong electric and magnetic fields in the neighborhood of the cyclotron.

One change from the original Dunning circuit is the provision of the gain control R_{14} in place of a fixed plate resistor in the third stage. This was made necessary because of the very large pulses from the fission fragments. These pulses were large enough to swing the grid of the fourth stage beyond the linear range and distorted the output. A further change, not shown in the diagram, was found necessary when dealing with the total ionization from both fission fragments. These pulses caused a similar effect in the third stage so the plate resistor R_7 was replaced by two 200,000-ohm, wire-wound resistors in series and the grid condenser, C_9, connected between them, cutting the grid swing of the third stage in half.

While the grid of the first tube is supposed to float near ground potential, more stability was found if a very high grid-leak resistance is used. A 2.4×10^9 ohm resistance was used. No measurable attenuation was found.

The heaters for the first two stages are supplied from a storage battery and those for the last two from a 2-volt A.C. transformer. The input voltage to the first two stages is 1.8 volts, but the line drop in the cable connecting with the first sta amounts to .3 volts, leaving only 1.5 volts for the first heater. This reduced heater voltage decreases the natural tube noise.

Power for the plates and screen-grids (+V) is supplied from a regulated-voltage unit. It is a circuit of essentially the same type as the high-voltage supply for the ionization chamber so is not described in detail. It was adjusted to supply a constant current of 11 ma. for all the measurements.

The dotted lines in the circuit diagram of Fig.25 indicate shielding compartments. When the amplifier was first built, these compartments were omitted and serious trouble was experienced with oscillations and pickup. The amplifier was therefore rebuilt with the more complete shielding and no more trouble was found.

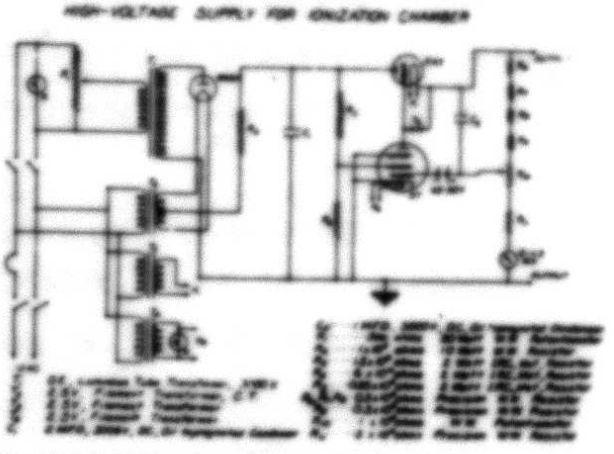


Fig.26--High-voltage supply for ionization chamber.

(2). Voltage supply for ionization chamber. The circuit of the high-voltage supply for the ionization chamber is shown in Fig.26. This is the well-known voltage-regulator type of circuit in which a pulse due to

a voltage fluctuation across the output resistors is inverted, amplified and fed back into the circuit. The constants for the circuit were chosen to give continuously variable positive voltages between 300 and 2600 volts. A 0-1.5 ma. meter in series with the 2-megohm output resistors forms a voltmeter with a 0-3000 volt range. The output of this circuit is connected to the ionization chamber by a high-tension ignition cable (Beldon #7777) which passes through the linear amplifier case and is enclosed with the other supply leads in the flexible conduit. The cable is completely shielded by braided copper sheathing. It is indicated by H.V. in Fig.25. Practically all fission experiments were made at 2400 volts. This exceeded the rating of the smoothing condenser (C_3 of Fig.25) by 400 volts but no breakdowns were ever observed.

(3). Current amplifier and recording oscillograph. A Dudell-type oscillograph (G.E. Cat. # 3859770G11) was purchased to record the size of the fission pulses. This is a bifilar galvanometer, consisting of a loop of phosphor-bronze ribbon stretched over an ivory bridge and placed in the field of a permanent magnet. The current to be measured travels in opposite directions in the two segments of the loop and therefore produces forces in opposite directions. A tiny mirror cemented to the suspension is used to record the deflections. The whole

unit is immersed in oil for damping. The galvanometer used is of the high-frequency type and gives a linear response up to 4000 to 5000 cycles. The resistance of the element is 0.8 ohms and its sensitivity is such that a 200 ma. current is required for 35 mm. deflection at 20 inches. In order to supply this comparatively large current, it was necessary to insert a current amplifier between the linear amplifier and the oscillograph. The circuit is shown in Fig. 29.

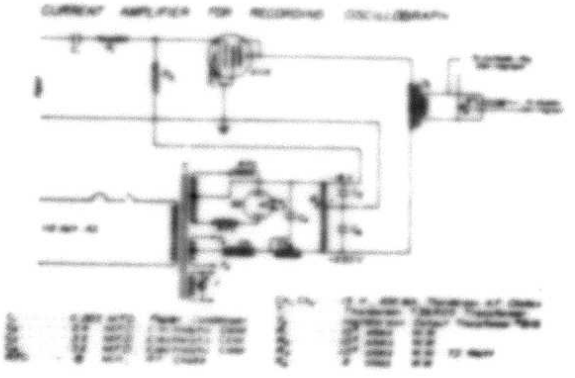


Fig.29--Current amplifier.

The circuit is essentially a single-stage amplifier with a transformer output but has an exceptionally well filtered power supply since small ripples in the supply would be recorded by the oscillograph. The resistance R_4 is connected into the circuit to supply a dummy load for testing purposes when the oscillograph is disconnected.

The use of a transformer output was questioned at first since its reactance might distort the pulses. However, the duration of the pulse is about one milli-

second, in other words, it corresponds roughly to 1000 cycles. This is the region of good audio response so it was reasoned that an output transformer which gives a best response in this region should also give good response for the pulses. The transformer output was therefore tried and found satisfactory.

The general arrangement of the recording oscillograph is shown in Fig.30, which shows it with the lid of the galvanometer compartment and the light-tight cover of the film compartment removed. Light from a 4.0-volt straight-filament lamp passes through condensing lenses and falls on the mirror of the galvanometer at the near end of the box. The beam is reflected through an aperture at the far end, passes through a cylindrical lens and is focussed on the film. No slits are used, the condensing lenses being adjusted to produce an image of the filament at the plane of the recording film. The axis of the cylindrical lens is parallel to the motion of the beam.

The film magazines, film track and driving sprocket can be seen in the photograph of Fig.31. The magazines are made from containers for 35 mm. bulk film. Slots are cut in the side of the can and lid and strips of copper cut and soldered to form lips. These are then covered with velvet to make light-tight slots. Photographic scotch tape is used to seal on the lids and to cover any suspicious joints. It was found necessary to install a takeup reel in the upper magazine. This consists of a

Fig.30--Top view of recording oscillograph with lid removed.

Fig.31--Film magazines and drive. Light beam enters from left between film magazines.

spool mounted on a shaft which extends through the wall of the film compartment. A pulley mounted on the shaft by a setscrew is driven from the sprocket shaft by a spring belt. The pulley ratios are adjusted so that some slippage always occurs, so the film is under a slight tension.

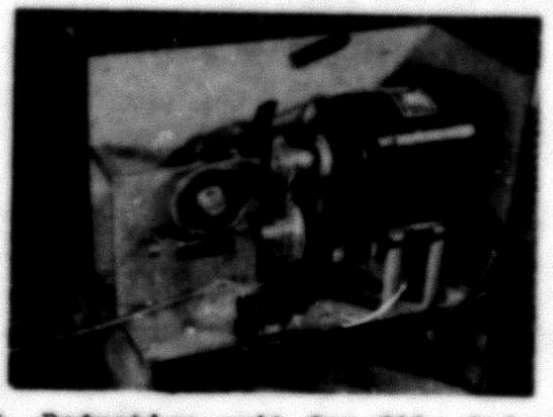


Fig.32--Reduction unit for film drive.

In Fig.32 is seen the reduction system for the film drive. The motor is a 1/150 H.P., 1800 R.P.M. synchronous motor. It drives a worm gear through a spring belt which can be placed on either of two sets of pulleys, giving 1:1 and 3:1 reduction ratios, respectively. The worm-gear reduction ratio is 100:1. The counter shaft finally drives the film sprock shaft through either of two sets of gears which give a 1:1 or a 4:1 reduction. There are thus several ranges of speeds between a low speed of 1.5 R.P.M. to 18 R.P.M. The lowest speed is used for most of the fission work and the highest for alpha-particle measurements. These speeds correspond to linear film speeds of 1/3 and 4 feet/minute.

The two banana plugs seen in Fig.30 beside the motor switch are connected to a 60-foot extension cord with a switch at the end. This is used to turn the motor on and off from the cyclotron control room which is located across the hall.

(4). Artificial-pulse generator. In order to check on variations in the gain of the amplifier between runs and to have a method of comparing the size of the fission pulses with those of the alpha particles, a series of pulses produced by known voltages was recorded on each film. The circuit for producing these artificial pulses was taken from the work of Kanner and Barshall (K-1). It is shown in Fig.33.

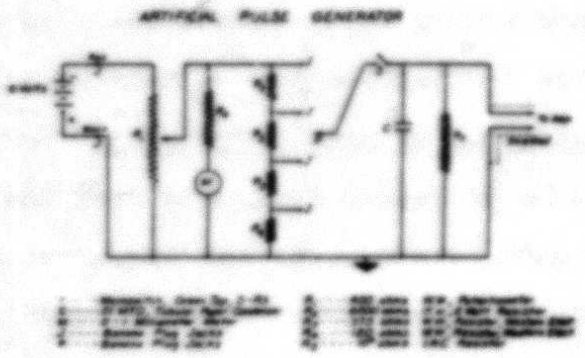


Fig.33--Artificial pulse generator

The resistance R_2 and meter M constitute a voltmeter measuring the total voltage across the four resistors $R_3 \ldots R_4$. The plug P can be inserted in the various jacks to place a known voltage across C when the switch S is closed. The sudden rise in potential across the output terminals as the condenser charges very nearly duplicates a pulse from the ionization chamber. The artificial pulse is applied to the grid of the first stage through a small condenser permanently connected.

The condenser consists of two 1/8" rods fitted into opposite ends of a 3/8" lucite rod, their ends being separated by about 3/8". One of the rods is soldered to the insulated contact of a jack mounted in the first-stage box and the other is connected to the grid of the tube. The output of the artificial-pulse generator is connected into a shielded cable with a plug to match this

jack. The jack is of the self-shorting type so the lucite condenser simply represents a small capacitance to ground during ionization chamber measurements.

(5). Preparation of uranium samples. For experiments in which only one of recoil fragments from the fission are to be recorded, the support for the uranium sample need not be thin, but the uranium layer itself must be very thin and uniform in order to prevent strong absorption of the fragments which originate near the bottom of the sample. Attempts were first made to deposit uranium oxide (U_3O_8) from suspension in a thin solution of rezoglaz in benzene or cellulose acetate in ethyl acetate. The resulting films were non-uniform and were inefficient in that the binder contributed at least half of the total stopping power.

The method of making the samples finally adopted is essentially the same as used by Simmons and Greene (not published) and by Jentschke and Prankl (J-1). A solution of about 0.5 gm. of uranyl nitrate in 1 liter of distilled water was used as the electrolyte. Strips of platinum ribbon were spot-welded together to form a grid about 5 cm. square and this is used as the anode. The cathode is a brass disk 5 cm. in diameter and 0.5 cm. thick. A current density of about 0.5 ma/cm^2 is used. During electrolysis the electrolyte is maintained at a temperature between 72° and 76° C. Constant agitation of the cathode is necessary to prevent the formation of bubbles. A

distance of about 5 cm. is maintained between the two electrodes. The time of electrolysis is calculated in the usual manner after the required number of atoms per square centimeter is determined. Experiment showed that the thickness of the layer obtained was always considerably less than that calculated in this way, even when allowance was made for the surface of the cathode hidden from the anode. The reasons for this will be discussed below. Actual electrolysis times were usually between 5 and 15 minutes.

Extreme care must be taken in preparing the brass surface if a uniform coating is to be obtained. The surface must be completely free from grease, dirt, oxide coating or other foreign material such as flecks of solder. For ease of manipulation, the brass disk is fitted with a handle consisting of a smaller disk to which a ¼" rod 3" long has been silver-soldered. This handle is soft-soldered to the back of the cathode with some care taken to center it. Then the handle can be chucked in a lathe and the front surface and rim of the cathode disk polished with fine emery and crocus cloth. The polished surface must never be touched with the fingers and the emery cloth should be fresh and as clean as possible. Clean tissue may be used to wipe off the abrasive powder. The disk should be put into distilled water immediately after being polished and should be left there until immersed in

the electrolyte. If the surface is properly cleaned, water should adhere to the surface and show no tendency to draw up into droplets. Another convenient test is to put the polished disk into dilute nitric acid for a few seconds and then observe the surface. Dirty spots will show up very easily.

During electrolysis the disk must be kept in motion and occasionally "bounced" on the surface of the electrolyte to remove the bubbles which form. After a minute or two, the surface should be examined for uniformity. Very brilliant interference fringes will show up on the wet surface and these can be used to give a very accurate estimate of the relative thickness of the different portions. Very often it will require several attempts to get a good surface. The old uranium layer may be removed by a short immersion in dilute nitric acid. In every case, there was a tendency for the uranium to deposit more strongly near the edge of the disk. This thick deposit extends only two or three millimeters from the edge so the practice is to continue the electrolysis if the deposit is otherwise uniform, then place the disk in the lathe and remove the thick layer with emery cloth. This does not cut down the effective area since the mounting ring in the ionization chamber masks off this area. It seemed safer, however, to remove this layer than to trust that it did not extend inside the guard ring. This thick peripheral deposit accounts for the discrepancy between

calculated and observed thickness mentioned above.

The final step in the preparation of the uranium layer is the oxidation to uranium oxide (U_3O_8). This is accomplished by heating the brass disk to a dull red heat for two or three minutes and results in a grayish-green layer with rather faint interference colors. In this process the handle used in all these manipulations is removed, also, and any surplus solder carefully wiped off.

For measurements of the ionization produced by both particles simultaneously, the supporting foil must have a very small stopping-power since one of the particles must traverse the foil before it can be recorded. Aluminum foil weighing .17 mg/cm^2 was used for this work. The foil is too fragile to be used unsupported so it is mounted on a grid in a manner similar to that used by Kanner and Barshall (K-1). Uranium should be deposited on the foil only on the holes in the supporting grid so the following procedure was followed:

Some pieces of heavy perforated copper were available in the laboratory. The .145" holes were punched in a square pattern 3/16" between centers. Two sections were cut out and matched to form a die. A .002" aluminum disk 2½" in diameter and a similar .020" disk were cut to serve as foil support and shield, respectively. These were clamped between the two sections of perforated copper and 39 holes punched by means of a hollow steel tool.

The pattern formed an approximate ellipse since the construction of the ionization chamber did not give the required 3 cm. clearance between the periphery of the disk and the electrode supports. The ellipse was later mounted with the major axis perpendicular to these supports.

The foil support was now cleaned and coated with dilute shellac. It was then carefully dropped on a selected piece of foil and allowed to dry for a few minutes. The shield could now be aligned and fastened to the other side by means of locating holes.

Electrolysis of uranium onto this composite foil was attempted with no success. Aluminum does not form a good base for electrolysis and the difficulties here were particularly great since the foil could not be cleaned. Evaporation of uranium metal from a tungsten spiral was also unsuccessful, the melting point of uranium being so high that more tungsten than uranium was deposited.

Finally, a sputtering chamber was arranged and this process used with success. The setup closely parallels that described by Van Voorhis (V-2). A small piece of uranium metal 5 x 10 mm. is gripped by the forked end of an aluminum rod suspended from the upper end of the sputtering chamber. The rod is protected by glass sleeving to limit the discharge to the uranium and has a right-angle bend at the lower end so the flat face of the uranium is parallel to the composite aluminum

foil. This foil is fastened on a water-cooled brass plate with the shield facing the uranium. The separation between the two is about 3 cm.

Fig.34--Sputtering chamber.

The general arrangement can be seen in the photograph of Fig.34. The vacuum chamber consists of a glass jar 6" in diameter and 13" long, closed at the ends by brass plates. The joints are sealed by rubber gaskets. The upper plate carries the support for the uranium. The plate itself is grounded and the high-voltage electrode insulated by a glass sleeve. The support rod is threaded into the electrode cap and can be raised or lowered by heating the wax joint and screwing the rod in or out. The lower plate is connected to the pumping system and to a flask of argon by separate leads. The anode is supported by the copper tubes which carry the cooling water. The

two brass studs extending about half-way up the chamber are not used in sputtering, so are protected by glass sleeves. They are included in the design so the chamber can also be used for evaporation. Voltage for the sputtering process is supplied by a rectifier set capable of 25 ma. at 8000 volts.

Because of the small uranium cathode and poor heat conduction from it, the current is limited to 5 ma. Argon is used as the sputtering gas. The pressure is not measured by is adjusted by watching the limit of the cathode dark space. This is maintained so that the area to be covered lies just inside the boundary. It is necessary to adjust the height of the cathode several times during the sputtering in order to obtain a fairly uniform coating. The uniformity of the layer can be judged by the interference fringes produced.

With this procedure a fairly uniform layer of 4×10^{17} atoms/cm^2 was formed in 4½ hours. The methods of calculating the thickness are discussed below.

(6). Shielding. Since parallel experiments were to be done with slow and fast neutrons it was necessary to use the cyclotron as a neutron source. Slow neutrons formed by slowing down the D-D neutrons from the neutron generator could be used for part of this work but the fast neutrons (13.6 Mev.) from the Li-D reaction are not available in sufficient quantities because of the low

energy of the deuteron beam.

As it was desirable to duplicate conditions as nearly as possible in the different runs, all measurements were made with the cyclotron. The Li-D reaction was used for fast neutron work and Be-D (3.8 Mev.) for the slow neutrons, paraffin and water being used in the latter case to produce thermal neutrons. Since the energy of the deuterons amounts to about 8 Mev., neutrons emitted in the forward direction have a higher energy than that calculated from the heat of reaction. The detecting chamber was put as nearly as possible in the direction of the beam to take advantage of this for fast neutron work and was placed at right angles to the deuteron beam in some of the slow neutron work to minimize the effect.

In order to get clear-cut results from the measurements on slow and fast neutrons, one should perform one experiment with only thermal neutrons present and one with only fast neutrons. In practice, it is only possible to arrange shielding in such a manner that the one type predominates--the other is always present as a background.

At least 15" of water or its equivalent is required to effectively remove the fast neutrons but Dunning (D-3) has shown that maximum slow neutron intensity is obtained with only a 4" thickness. Beyond this thickness, the intensity decreases rapidly because of absorption. Unless the original neutron intensity is very high, one must use some intermediate thickness. In the experiments

to be described, a 9" slab of paraffin was usually used between the cyclotron target and the ionization chamber.

The cyclotron room is lined with water tanks and water circulates in the magnet coils immediately above and below the target so there is a profusion of slow neutrons present during any deuteron bombardment. In order to eliminate as many of these as possible when working with fast neutrons, the ionization chamber was enclosed in cadmium. The back of the chamber was permanently covered with cadmium sheet and the sides and front were fitted with a removable cap. Since cadmium stops only thermal neutrons, a square box built up of 2" slabs of cast paraffin and borax was placed around the chamber, leaving only the front face exposed. The back of this box is formed by the block seen in Fig.24. It is left on permanently. The other sections were removed for the slow neutron measurements.

Finally, this entire assembly was placed inside a structure of 5-gallon water cans. A side view of the completed unit is seen in Fig.35 where one can has been removed to show the position of the ionization chamber. The black box seen in the opening houses the first stage of the amplifier. The ionization chamber is mounted on it and faces the cyclotron target. The large block of paraffin placed between the target and chamber for the slow neutron work is seen on the lower shelf of the rolling table supporting the water cans.

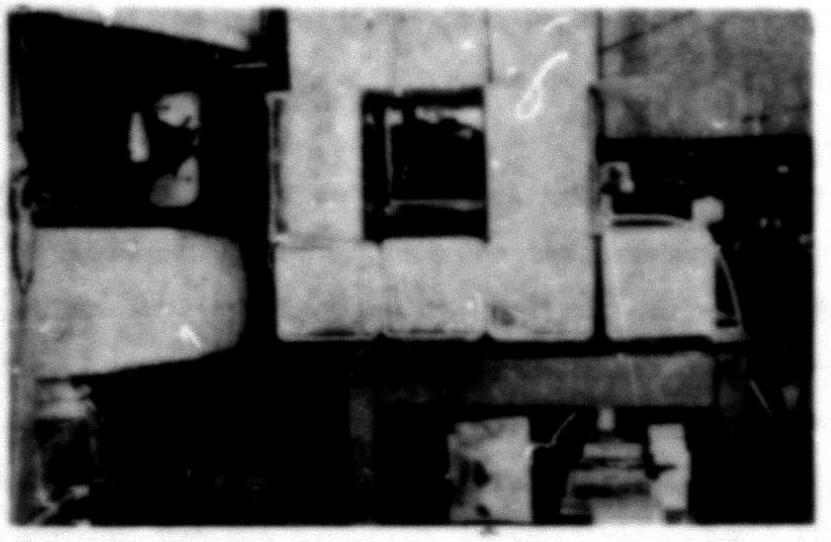


Fig.35--Neutron shielding for fission experiments.

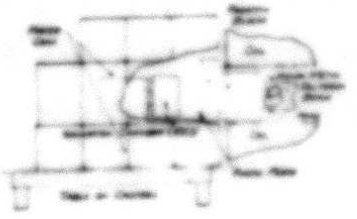


Fig.36--Relative position of target and ionization chamber.

The relative position of the ionization chamber and the cyclotron target, as seen from the side opposite that of the photograph of Fig.35, is shown in the sketch of Fig.36. The photographic plate indicated in the sketch is a special plate used by W.A.Miller, who co-operated in these bombardments and is separately reporting his work on

fission tracks recorded on photographic plates.

Typical procedure in making a bombardment is illustrated by the following:

The linear amplifier is turned on and about one minute allowed for heaters to warm up before turning on the high-voltage for the ionization chamber. The filament voltage for the first two stages is adjusted to 1.8 volts. The amplifier is allowed to run for at least one hour before any measurements are taken. This interval is occupied by threading the film in the recording oscillograph, inserting the proper target in the cyclotron, putting the ionization chamber in place and starting up the cyclotron.

After the cyclotron is started and the beam tuned in, all voltages on the linear amplifier are checked and the gain (R_{14} of Fig.27) is adjusted for proper pulse size. This is done by observing the size of the kicks in the cathode-ray oscillograph. For convenience, a line is made on the screen corresponding to full-scale deflection of the recording oscillograph.

The remote-control switch for the film-drive motor is now brought into the cyclotron control room and the linear amplifier setup requires no more attention until the completion of the first run. From five to twenty minutes is allowed per run, the time being estimated to give at least 600 pulses.

At the end of a run, the cyclotron oscillator is

turned off and the artificial pulse generator plugged into the first stage of the amplifier to put on the calibration. Five pulses of each size are recorded in a series which covers the range of measurements in 6 to 8 equal voltage increments.

The necessary changes in neutron shielding are effected and the next run made in a similar manner, followed by a calibration. At the conclusion of the fission runs, the film speed is increased, the gain of the amplifier reduced and a short record of the uranium alpha particles made, followed by its calibration.

In most of the work, three series of runs were made so the bombardment schedule was the following:

(a). Li-D neutrons, Cd + borax shielding on chamber.

(b). Calibration: 6.0, 5.4, 4.8 .....0.6 volts.

(c). Li-D neutrons, 9" paraffin block.

(d). Calibration.....

(e). Be-D neutrons at right-angles, 9" paraffin block.

(f). Calibration.....

(g). Uranium alpha particles.

(h). Calibration: .23..... .03 volts.

The order of the bombardment was varied to insure that variations in the results could not be due to a systematic drift in the sensitivity. No such change was ever found if the warmup time of the amplifier was not made too short. The calibration pulses for the various runs check one another within 4%, which is near the limit of accuracy

of the voltage settings. These would also be reproduced from bombardment to bombardment for the same gain settings, indicating good stability in the amplifier.

The calibration pulses also served as a check on the over-all linearity of the amplifier. A plot of deflection against voltage should yield a straight line if the amplifier is strictly linear. This was far from true with the first experiments and yielded distorted distribution curves. Several hours of experimentation indicated that it was futile to attempt readjustment by trial and error since readjustment of any one of the four bias controls changed the voltage distribution on all stages of the amplifier.

The method which furnished a quick and satisfactory solution to this problem consisted of matching the shape of the approximate sine wave produced by a 1000-cycle tuning fork at the input and at the various stages of the amplifier. The oscillator is the ordinary "howler" used in the intermediate laboratory. Its output was first connected directly to the cathode-ray oscillograph and the wave pattern traced on the screen by a china-marking pencil. The howler was then plugged into the first stage through the artificial-pulse condenser and the C.R. oscillograph plugged into the linear amplifier output. The effect of the various bias changes was readily seen by comparing the amplified wave with the original tracing. Adjustments were made until the image coincided with the

trace.

By adjusting the gain of the amplifier it was possible to go through this procedure without changing the gain control on the C.R. oscillograph so a non-linearity in its response has no effect. The voltage output of the current amplifier was too small to permit this same direct check, but tests across the primary of the output transformer indicated no distortion.

This method of adjustment, of course, only insures linearity for the single frequency of 1000 cycles/sec. However, tests with artificial pulses after adjustment show a linear response so the amplifier cannot be very sensitive to frequency changes in this range.

(7). Measurements on recording films. Because of the low light intensity and the short duration of the pulses, it is necessary to use a fast panchromatic film* for recording. At the conclusion of a bombardment, the film magazine is removed bodily. The film is cut into 5½-foot lengths and loaded into roll-film tanks in complete darkness. The development and fixing can then be done in the light. The films are developed for 5 minutes in undiluted D-72, rinsed, fixed in acid hypo for 10 minutes and washed in running water for 20 minutes.

Two different methods were used for measuring the height of the pulses. At first, the film was viewed

# # # # # #

* Agfa Ultraspeed, 35 mm.

through a magnifying glass as it was pulled through a special holder provided with a steel scale set parallel to the direction of the pulses. As each pulse was brought up beside the scale, the millimeter interval in which it ended was called out to an assistant who kept a record by the tally system. The calibration pulses were averaged and recorded to the nearest fifth of a millimeter. This method was quite accurate but tedious. It required a helper and fatigued the eyes of the person reading the film.

Fig.37--Projection method of reading recording film.

The second method consisted of projecting an enlarged image of the film on a screen ruled into suitable intervals. The setup used is illustrated in Fig. 37. A 35 mm. projector placed on the work table is aimed at a small plate-glass mirror set at approximately 45°. The light is

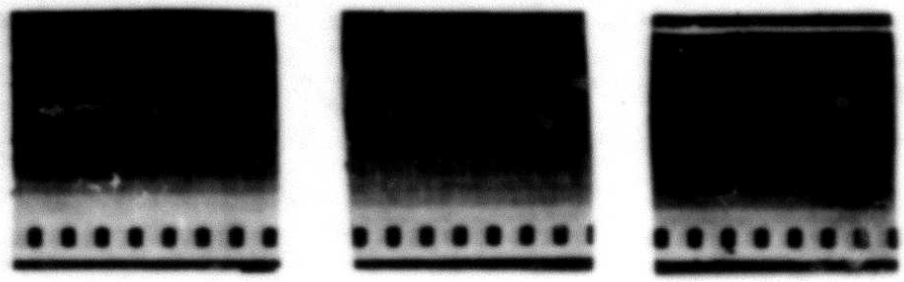
reflected from this mirror to a larger mirror hung horizontally above the table. From this, the light falls on a large sheet of drawing paper on the table in front of the operator and forms an image approximately 50 x 75 cm. The paper is ruled into 2 cm. intervals which are numbered consecutively from 0 to 25. Since the width of a 35 mm. film between perforations is 25mm., the magnification amounts to 20 x and the intervals correspond to the 1 mm. intervals used in the first method.

Space is provided on the end of the drawing board nearest the operator to tack down a strip of paper on which the pulses are tallied as observed. The original mask in the projector was replaced by a larger one which made the sprocket holes visible in the image. The zero was maintained by aligning the edge of the sprocket holes with the zero line of the drawing board.

The projector method proved far superior to the first method. Only one person was required and he could record a film in about the same time required by two persons by the old method. Eye fatigue was also greatly decreased.

With either method, the accuracy is independent of the position of the undeflected beam since all measurements are referred to the standard calibration pulses. Advantage is taken of this fact to increase the resolution of the method by setting the zero of the galvanometer to a few millimeters off the edge of the film.

C. Results from fission experiments. (1) General. Contact prints from typical films are shown in Fig. 38. Fig.38-a shows pulses from single fragments obtained by bombarding uranium on a thin foil with slow neutrons, the back of the foil being covered to stop the second particle. Two groups of pulses are clearly seen. In Fig.38-b are seen pulses from the uncovered foil in which both particles are recorded. One group of pulses only is seen with the exception of a few scattered smaller pulses due to single particles. Fig.38-c shows part of a calibration run taken in connection with the total ionization experiment. The first and second films are not directly comparable since different gain settings were used.



(a) (b) (c)

Fig.38.--Typical sections of recording film. (a)--Single pulses from Be-D neutrons slowed to thermal energies; (b) total ionization from thin foil with fast Li-D neutrons; (c) calibration pulses.

Considerable definition has been lost in the prints. It is, however, possible to see the individual pulses and the general illumination along the lower edge of the film from the undeflected light beam. The beam itself is considerable narrower than indicated, the apparent broaden-

ing being due to halation in the film and lack of latitude in the printing paper. It is possible to make measurements from the film itself on pulses within 2 mm. of the sprocket holes.

The heights of the pulses are recorded in the manner already described and are tabulated according to the interval in which the pulse ends. On the next page is shown such a tabulation, together with the calibration pulses inserted between the runs.

The results are now plotted on coordinate paper as shown in Fig.39. Since there is a possibility of assigning a pulse to the wrong interval when it lies on the boundary, the curves were smoothed by averaging each successive pair of readings and plotting the result at a point midway between them. In this way, only peaks which extend over two or more intervals are given significance. This also has a slight tendency to broaden the peaks, but probably presents a more accurate picture than the more jagged curves which would be formed from the plot of the single measurements.

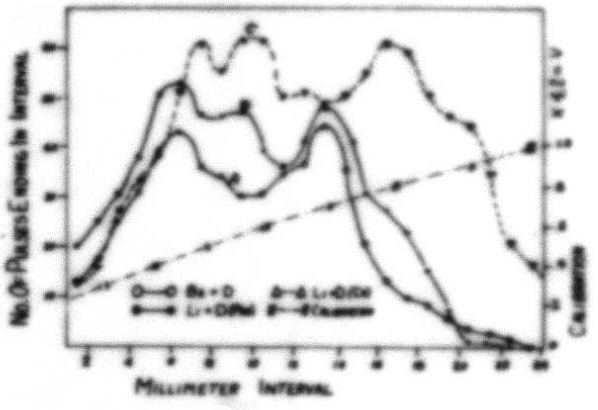


Fig.39--Pulses produced by single recoil fragments.

(Typical tabulation of film readings.)

Film (4-9-41) Single particles

Argon gas Gain set at 19

Column I--Millimeter interval;

Column II--Fast neutrons, Li-D, cadmium filter;

Column III--Mixed neutrons, Li-D, 9" of paraffin, no filter;
Column IV--Slow neutrons, Be-D, 9" paraffin.

I	II	III	IV
		17	12
1	14	23	14
2	12	27	21
3	20	34	29
4	34	28	33
5	33	48	46
6	43	53	40
7	59	53	32
8	63	40	36
9	47	52	24
10	76	42	37
11	47	36	32
12	53	36	41
13	49	46	47
14	48	50	24
15	53	37	17
16	57	26	9
17	65	28	10
18	52	17	6
19	49	13	5
20	43	1	2
21	45	0	3
22	22	1	0
23	19	0	0
24	13	0	0
25	3	0	0

(Typical tabulation of film readings, cont.)

Calibration

Pulses from artificial pulse generator. V. is proportional to the voltage impressed on input condenser. II, III, and IV are the observed pulses for the three calibrations corresponding to the runs just listed.

V.	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
II	23.4	20.7	17.0	13.8	10.7	7.9	5.4	3.0	0.5
III	23.5	20.6	17.1	13.7	10.8	7.8	5.2	3.0	0.3
IV	23.4	20.6	17.0	13.8	10.5	7.8	5.3	2.6	0.3

Many of the early runs were distorted by the non-linearity of the setup, part of which was in the amplifier itself and which was later corrected by tests with 1000 cycles, as already described.

The data from these runs could be used by applying suitable corrections. The non-linearity is evidenced by a curved calibration curve. It also produced a distortion in the relative heights of the peaks. For slow neutrons, the areas under the peaks for the light and heavy fragment should be the same since there is an equal probability of either emerging from the uranium layer. Since plots were made of numbers of pulses versus observed pulse size, if the energy range per millimeter deflection is not constant over the range, too many or too few pulses sill occur per millimeter. To correct this, a new plot must be made by the following method:

An integral curve is made with the total number of pulses having a length equal to or greater than the abscissa plotted against the deflections as abscissa. On the same sheet one plots the calibration curve. The integral curve is now differentiated graphically by taking the successive differences of points corresponding to equal increments in voltage. The data thus obtained is then replotted to give the corrected number-voltage curve. A test of the correctness is a comparison of the relative heights of the two peaks produced by slow neutrons.

The method is rather tedious so was used only in the cases where a definite non-linearity was seen. The actual position of the peaks as measured against artificial-pulse voltage is unchanged. In the measurements used in the final results, the curvature of the calibration curves, if apparent, is very slight, so the replotting was unnecessary. All measurements, however, are referred to the corresponding voltage instead of to the deflection itself.

Distortion of the peaks which did not correspond to corresponding curvature in the calibration pulses was also observed in the early runs. This, together with the fact that the energies of fission fragments were much too low when calculated from the observed pulses of uranium alpha-particles, made it apparent that the ionization chamber was not being saturated with the applied voltage.

Air was then being used in the chamber. Increasing the voltage from 1900 to 2400 volts increased the size of the fission pulses but still gave insufficient energy. Changing to dry nitrogen, flowed through the chamber continuously during a run, increased the size of the pulses by a factor of three and brought the energy into reasonable agreement with that calculated from the alpha-particles.

When making runs with fast neutrons, pulses large enough to disturb the fission measurements were observed. This was thought to be due to recoils of the nitrogen nuclei from elastic collisions with neutrons in the ionization chamber, so argon was substituted for the nitrogen. This eliminated the extraneous pulses and somewhat increased the absolute size of the fission pulses.

Calculations based on elastic recoils give the maximum recoil energy as $4mM/(m+M)^2$ times the incident energy. For 17 Mev. neutrons, the recoil energy of nitrogen nuclei is only 4.2 Mev. Since this is about the energy of the uranium alpha particles, the observed pulses must have been from hydrogen, present as an impurity, for which the maximum energy could be the full 17 Mev.

Argon was used for the remainder of the experiments for the above reasons and because its recombination time is long, insuring that all the ions formed will have time to be collected before recombination. It was inconvenient

since the chamber had to be evacuated, flushed and refilled each time a change was made in the uranium layer. The other alternative was to use air in the chamber at a much higher voltage. Neither power supply nor chamber would permit this without complete redesign.

(2) Calculation of uranium thickness. The thickness of the uranium films was calculated by counting the number of alpha particles recorded on a measured length of film. From the known film speed, the number of alpha particles per second is found. Using the decay constant for uranium, the number of atoms is calculated, from which, finally, the mass per square centimeter can be obtained.

For the film electrolyzed on a brass disk for the single-particle measurements, 363 tracks were counted on 30 cm. of film. The corresponding time is 15 seconds, giving 24 alpha particles per second. Since only half of the alpha-particles can be detected, the true number of alphas is 48/sec. These come in equal numbers from U_I and U_{II}. We are only interested in the stopping power so the alphas from U_{II} should not be counted since the relative abundance of U_{II} is only 0.008% and it does not contribute appreciably to the stopping power. This again gives 24 alphas/sec. The coating on the disc occupies an area of 12.5 cm^2, giving approximately 2 alphas/sec/cm^2.

The disintegration constant of U_1 is 4.7×10^{-18}/sec. N, the number of uranium atoms per $cm.^2$, must therefore be

$$N = 2/4.7 \times 10^{-18} = 4.3 \times 10^{+17} \text{ atoms/cm}^2.$$

The film is actually made up of U_3O_8. Direct calculation thus gives a density of .21 milligrams/cm^2.

Similar calculations on the film sputtered on the .17 mg/cm^2 aluminum foil yield a density of 0.18 mg/cm^2, based on the following data:

Number of alphas from front surface=549 in 60 sec.

Number of alphas from back surface = 407 in 57 sec.

Uranium deposited in 39 disks, each .37 cm. in diameter
Total area = 4.2 cm^2

Alphas/cm^2/sec from one side = 2

Density of metallic uranium = 0.18 mg/cm^2.

The difference in density in the two cases when the same number of alpha-particles are observed, is due to the effect of the oxygen in the uranium oxide.

The air equivalent of these films can only be estimated since the relative atomic stopping power of uranium is not known. For lighter elements the relation $s = 0.563\ Z/(Z - 10)^{\frac{1}{2}}$ is valid. This gives a relative stopping power for uranium of 5.2. The heaviest element for which good measurements have been made is gold. (B-3, page 272). The value given for 4.66 Mev. alpha particles is 3.96. The above formula gives 4.45 which is about 15% too high. On this basis the relative stopping power of uranium should be about 4.4.

If this value is assumed, the air equivalent of the two films are 1.0 and 0.7 mm., respectively, the air

equivalent of oxygen being about unity.

These values are somewhat higher than those obtained by comparison with Kanner and Barshall's results. Their uranium layer had a density of .12 mg/cm^2 to which they assigned a stopping power of 0.3 mm. of air. On this basis the .18 mg/cm^2 sputtered uranium layer should have a stopping power of 0.45 mm. instead of 0.7. The basis for their calculations was not stated.

The question of the air equivalent of the uranium foils for the fission fragments cannot be answered as yet. The whole matter complicated by the fact that the energy loss of the fission fragment in passing through a given thickness of any material will depend upon the distance of the absorber from the beginning of the range. The fragment is initially highly charged and loses its charge during the stopping process so it is to be expected that the energy loss will be greatest near the beginning.

Knipp and Teller (K-3) have extended the calculations of Bohr (B-6) on range-energy relationships for fission fragments to calculate the electronic and nuclear cross-sections for the light and heavy fragments in air. Their calculations show that the electronic cross-section increases enormously near the beginning of the path. Lark-Horovitz and Miller (L-3) have also shown this to be true in photographic emulsions from the grain-spacing

observed in fission tracks recorded in special plates.

If one takes the cross-section at the beginning of the range, as calculated by Knipp and Teller, and assumes that the relative stopping-power of uranium is 4.4 times that of air, an estimate of the energy loss of the fission fragments which originate at the bottom of the uranium layer can be made. For the light fragment, the cross-section is approximately 2.8×10^{-18} Mev. $-cm^2$. Multiplication by 4.4 is assumed to give the cross-section for uranium. The number of atoms/cm^2 is 4.3×10^{17}. The product is 5.4 Mev. For the U_3O_8 layer, the energy loss amounts to about 7.6 Mev.

For the heavy fragment, the cross-section is initially somewhat higher but decreases rapidly so the average over the uranium layer will be about the same.

These values are much higher than those estimated by Kanner and Barshall. They assumed that the rate of energy loss was the same over the entire range and amounted to about 1 Mev. for the uranium layers used. With the above estimates, this should be about 3.5 Mev.

It is not possible to test the accuracy of the new estimates from the observed half-width of the peaks since the variety of elements identified chemically from each group indicate a considerable spread in masses. This leads to a corresponding spread in the energies of the single particles.

(3) Single particles from slow neutrons. The first check made on the results was a comparison of the curves of the single fragments from slow neutron bombardment with those of Kanner

and Barshall (K-1). Two different curves taken under quite different conditions were selected. The result is shown in Fig. 40.

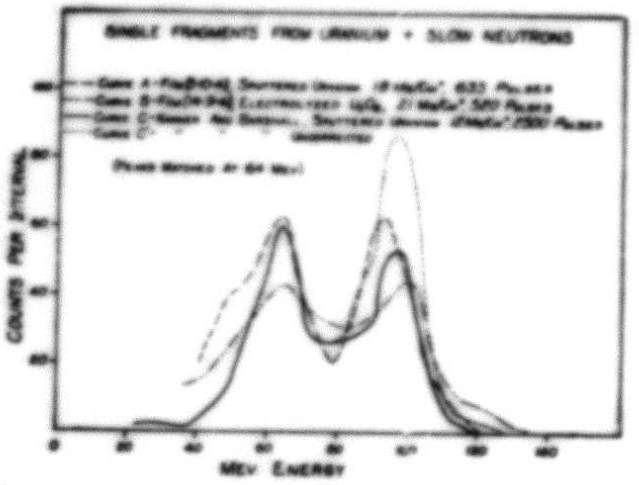


Fig.40--Comparison of results with those of Kanner and Barshall.

Curve A was taken with the sputtered layer of uranium on thin aluminum foil bombarded with thermal neutrons from the Be-D reaction, the direction of observation being at right angles to the deuteron beam. The film was read with the projector setup. Curve B was taken with the electrolyzed layer on a brass disk, bombarded with thermal neutrons from the Be-D reaction with the observation in the direction of the deuteron beam. The film was read directly with a magnifying glass. Curve C is copied from the article by Kanner and Barshall. The dotted portion of the curve is the corrected portion which they replotted to correct non-linearity in their oscillograph. (cf. discussion above on non-linearity.)

The curves were arbitrarily matched at 64 Mev. The

value given by Kanner and Barshall for the higher peak is 97 Mev. The two values from the present measurements are 92 and 99 Mev. Quite good agreement is therefore found. The fact that the valley of curve B is not as deep as those of the other two is explained by the difference in the geometry. In curve B, the ionization chamber was placed in front of the cyclotron target. The neutrons emerging from the beryllium target in this direction have an added energy due to the transfer of momentum from the 8 Mev. deuterons. As will be shown in the next section, this increases the maximum energy of the neutron by 1.6 Mev., making a total of 5.4 Mev. In curve A, the neutrons emitted at right-angles to the deuteron beam were used, for which the energy is 3.8 Mev. If symmetrical fission sets in at an energy intermediate between these two, the increased height of the valley is accounted for. Paraffin was used in both experiments, which slows down most of the neutrons, but an appreciable number can reach the uranium layer with their original energy. It is to be noted that the tails of curve B at both the high and low energy ends extend farther than in curve A. Highly asymmetrical fission produced by the faster neutrons will also account for this.

The curve of Kanner and Barshall was taken with D-D neutrons produced by low-energy deuteron beam. The neutron energy thus has a maximum of 2.4 Mev. and no fast neutron effects are to be expected.

(4). Single particles--Effect of increased neutron energy. It was stated earlier that it had been expected that higher

neutron energies would tend to fill in the valley between the two peaks observed for slow neutrons. To make a direct check on this, each bombardment included three runs: (a) Slow neutrons to establish the two main peaks; (b) fast neutrons from Li-D partly slowed by interposition of paraffin, and (c) fast neutrons from Li-D with slow neutrons filtered out with Cd + Borax.

The results of two independent series of runs are shown in Fig.41 and Fig.42. The first curve is the one of Fig.39, normalized to the same total number of counts for each of the curves A, B and C, and plotted in terms of Mev. of energy. The energy units are obtained by setting the low-energy peak of curve A at 64 Mev. and using the calibration curve to determine the energy scale. The measurements were taken with the U_3O_8 layer already described. Runs A and B were taken with 13" of paraffin between target and chamber.

Fig.42 shows three similar curves obtained with the sputtered uranium film on aluminum foil, the back of the foil being masked by a thick aluminum sheet. Because of the smaller amount of uranium, only 9" of paraffin were used in runs A and B to decrease the absorption of slow neutrons and give larger yields.

Data for curve A of Fig.41 was taken with the neutrons projected in the line of the deuteron beam and that of Fig.42 was taken with neutrons emitted at right-angles to the beam. As already discussed, this results in different

neutron energies. This, together with the differences in the paraffin filters, accounts for the variations in heights of the corresponding peaks in these two curves.

In both figures, run C was made with the fast neutrons projected in the forward direction of the deuteron beam.

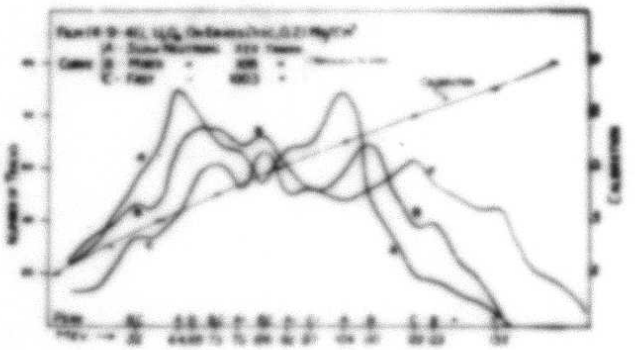


Fig.41--Single recoil fragments.
Electrolyzed U_3O_8 layer.

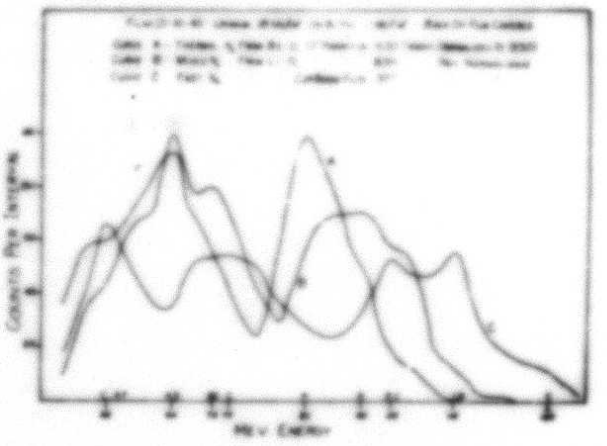


Fig.42--Single recoil fragments.
Sputtered urenium layer.

It is apparent from these two curves that some new

process must be entering as the neutron energy increases. If no new process is assumed, one should expect to find only a broadening and shifting of the peaks to higher energies because of the added energy of the incident neutrons. The magnitude of the expected effect of this can be calculated:

The maximum energy of the neutrons from the Li(d,n)2α reaction is 13.6 Mev., as observed from proton recoils in a cloud chamber by Bonner and Brubaker (B-7). The neutrons were observed at right-angles to the 0.85 Mev. deuteron beam.

In the present case, the energy of the deuteron beam is about 8 Mev. and the neutrons projected very nearly along the line of the deuteron beam so their energy should be somewhat higher. The maximum neutron energy can be calculated by the following procedure:

If we consider the process to take place in two steps, the first one is the inelastic collision of an 8 Mev. deuteron with a stationary Li nucleus. Applying the conservation of momentum:

$$M_d V_d = (M_d + M_L)\, V_c$$

where M_d and V_d refer to the mass and velocity of the incident deuteron, M_L is the mass of the lithium nucleus and V_c is the velocity of the compound nucleus.

Putting in the masses, $M_d = 2$ and $M_L = 7$ and solving for V_c,

$$V_c = (2/9)\, V_d$$

The energy of the deuteron $E_d = \frac{1}{2}M_d V_d^2 = 8$ Mev.

from which

$$V_c = (2/9)\ 8^{\frac{1}{2}}$$

The second step of the reaction is the splitting of the compound nucleus into a neutron and two alpha-particles. The neutron will have a maximum velocity if the two alpha-particles are emitted in the same direction and reverse the path of the deuteron, the neutron being projected ahead.

From the observed maximum neutron energy $E_n = 13.6$ Mev., the velocity of the neutron in a center-of-gravity system can be calculated.

$$E_n = \frac{1}{2}M_n V_n^2 = 13.6; \quad V_n = (27.2)^{\frac{1}{2}} \quad (M_n = 1)$$

The total velocity of the neutron in a stationary system will then be

$$V_n' = (2/9)\ 8^{\frac{1}{2}} + (27.2)^{\frac{1}{2}}$$

and the total energy

$$E_n' = \frac{1}{2}\ V_n'^2 = \frac{1}{2}\ (5.85)^2 = 17 \text{ Mev.}$$

A similar calculation for the Li(d,n)B reaction gives

$V_c = (2/11)\ 8^{\frac{1}{2}}$; $E_n = 3.8$; $V_n = (7.6)^{\frac{1}{2}}$; $V_n' = 3.3$

and finally

$$E_n' = 5.4 \text{ Mev.}$$

One would expect the effects of thermal neutrons to predominate in curves A and B, since paraffin filters were used, with minor effects due to the residual fast neutrons in A but larger effects in B because the original neutron energy is higher. In curve C the fast neutrons predominate because of the cadmium and borax filter.

Without the assumption of new processes, then, one would expect to find an increased total energy of 17 Mev. in curves B and C which would be divided between the two particles. Since the fission particles have masses in the ratio of 3:2, this energy would be split in the inverse ratio, giving about 7 Mev. to the heavy particle and 10 Mev. to the light particle. Since all intermediate neutron energies are also present, the result should be a broadening of the peaks and a shift of the maxima to higher energies.

Referring to the curves, one does find such shifted peaks in curves B in addition to components corresponding to the peaks of curves A. There are, however, additional peaks entering which cannot be correlated as easily. In the curves C, the differences are more pronounced, the slow neutron peaks being diminished or completely absent while new peaks appear.

There are some discrepancies between the two sets of curves, both in peak position and relative peak height. The shifting of the peaks is inside the overall experimental errors plus the broadening due to absorption in the uranium itself. The change in relative heights can be accounted for by differences in slow neutron "leakage" in the two setups.

At the bottom of each of the figures is a listing of the various peaks as calculated from the calibration

curve after assigning the low-energy peak of slow neutrons as 64 Mev. Above each energy is given the curve for which the peak exists.

The reality of the peaks can be checked by eliminating any which do not appear on both curves. If this is done, the following peaks remain (energies in Mev.):

Peak No.	1	2	2f	3	4	4f	5	6
Curves A								
Fig.41:		64			92-104			
Fig.42:		64			92-105			
Curves B								
Fig.41:	52	68----73		86		-----110	123	
Fig.42:	52	64	73--80		-100--105-		118	
Curves C								
Fig.41:	52		73	86		110	120	135
Fig.42:	52		-75----			105-	118	130

Dashes are used to indicate broad distributions which cover the region of the corresponding peak on the other figure.

As a tentative explanation of these peaks, assume the following:

(a)-Peaks 2 and 4 of curves A, which are the ordinary slow neutron peaks due to the asymmetrical fission of U^{235}, are also found in curves B. In curves B and C is found a second group of peaks (2f,4f) which represent a fission of the same asymmetry but with a shift to higher energy. This might be due to the asymmetrical fission of U^{239} which is calculated to have a threshold at 0.7 Mev. (B-4).

(b). Peak 3 is assumed to be a doublet representing symmetrical fission. The chemical experiments of Yasaki (Y-2) and Segré (S-2) have shown that the elements in the middle of the periodic table are produced only when fast neutrons are used.

(c). Peaks 1 and 5 of curves B and C represent a new mode of highly asymmetrical fission which is produced only by fast neutrons.

(d). Peak 6 must represent some type of fission which is produced only by fast neutrons and which has a smaller cross-section since it did not appear in curves B. If it represents the emission of two particles from a ternary fission, there should be a corresponding peak for a single particle at about 66 Mev. This would probably be masked by the general overlapping. It is true that the general level of the curve in that neighborhood is higher in Fig.41 than in Fig.42, while peak 6 is also more pronounced in Fig.41.

From the law of conservation of momentum, the product of the mass and energy must be the same for the two particles in a binary fission. This, together with the known total mass, makes it possible to estimate the masses of the fragments for these various modes of fission. Correlation with chemical experiments should then be possible.

Peaks 2 and 4 give the ratio 1.5, leading to masses of 140 and 95. Since this is the slow neutron peak the

chemical evidence is in abundance.

Peaks 2f and 4f give the same ratio of 1.5. If these are assigned to U^{239}, the difference in masses is too small to distinguish them from the slow neutron elements.

Peaks 1 and 5 give a ratio of 2.3, leading to masses of about 170 and 70. These masses lie beyond the range of the elements found in slow neutron work. However, Nishina and Yasaki (N-1) found both mercury and bismuth in chemically-separated fractions from uranium bombarded with fast Li-D neutrons. These indicate even higher asymmetry.

Peak 3, interpreted as a doublet representing symmetrical fission, gives masses of about 120. As already mentioned, Yasaki has completed the series through the middle of the periodic system in his work with fast neutrons and has shown that these elements are not found with slow neutrons. Segré has confirmed his work and extended his identification of the isotopes.

Peak 6, assumed to be triple fission, will give masses in the neighborhood of 80. Since this overlaps with ordinary asymmetric fission, such elements are found but this does not constitute a proof for its existence.

From the chemical evidence, therefore, there is definite proof for the symmetrical type of fission and no contradiction in assuming triple fission. The highly asymmetrical fission was found only with fast neutrons,

confirming the evidence from the distribution curves.

5. Comparison with total ionization from thin foil. The total energy of the peaks assumed to be coupled must check with the observed energies if a thin foil is used to permit all the fission fragments to emerge into the ionization chamber. Such measurements were made but the results are restricted to low energy limits only due to an experimental error which was discovered too late to remedy in the limited time available.

The measurements were made in the usual manner, using pulses from the artificial pulse generator to check the linearity. These pulses extended just past the high-energy peak and indicated no non-linearity. Later, the question of the existence of smaller peaks of higher energy was raised and the linear amplifier checked for response to still larger pulses. It was then found that a sharp cut-off existed at a pulse size corresponding to the limit of the high-energy tail observed. Interpretation of data on total ionization must therefore be limited by this fact.

The curves of Fig.43 are lettered to correspond to those for the single fragments. A progressive shift toward higher energies is seen as the neutron energy is increased.

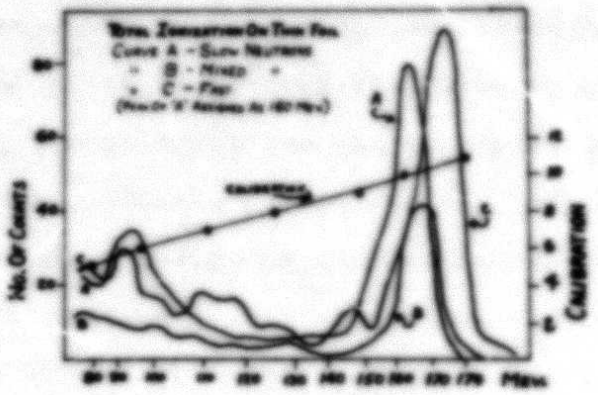


Fig.43--Total ionization from uranium sputtered on thin aluminum foil.

Adding the energies of the peaks assumed to be coupled in the previous discussion, the following values are obtained:

For A:	(2,4)	156 to 169		
For B:	(2,4)	----------(2f,4f)	159 to 183;	
	(1,5)	170 to 175;	(3,3)	172
For C:	(2f,4f)	170 to 182;	(1,5)	168 to 170;
	(3,3)	172 ;	(6,6)	190 to 200

Comparison of the curves of Fig. 43 with the above calculations indicates that the energies corresponding to the central maxima are actually found but that the spread of energies is less for total ionization than would be predicted from the single-fragment measurements. This is quite independent of the non-linearity restrictions already mentioned since the steepness of the peak on the low-energy side is not subject to these limitations. It is believed that this is good evidence for a large ab-

sorption of energy by the uranium layer itself. In the case of the single particles, an energy spread equal to the total stopping power of the uranium layer is to be expected, since the fragment may originate in any part of the layer. In the case of total ionization, if the stopping power is assumed to be approximately the same for the different fragments, the total thickness of material traversed by the two particles is constant--except for those which emerge at oblique angles.

Regarding triple fission peak (6,$\frac{1}{2}$6), not much can be said from the total ionization curve due to the cut-off of the amplifier. The fast neutron curve does still show a high-energy tail which is required only by the triple fission. This is not found in the other two curves, in agreement with the absence of triple fission in the single-particle curves A and B.

The minor peak in curve C at about 145 Mev. is not yet understood. Comparison with the C curves of Fig.41 and Fig.44 shows that similar small peaks occur at about the same energy, indicating that this should be due to single particles. However, no such peak is found in Fig.42. There were two off-scale pulses found in this run which are not recorded. This number is too small to be of significance. The matter requires further investigation.

Present's calculations on the heat of reaction of triple fission (P-3) indicate about 20 Mev. more energy than for binary fission. The value assigned here, 190 to

195 Mev., agrees closely when the energy or the incident fast neutron is taken into account.

(6). Stopping power measurements. A series of runs was made with a setup which duplicated as nearly as possible that of Fig.42* with the one change in that the front of the foil was shielded so that only single fragments which had traversed the aluminum foil supporting the uranium layer were recorded. The results are shown in Fig.44.

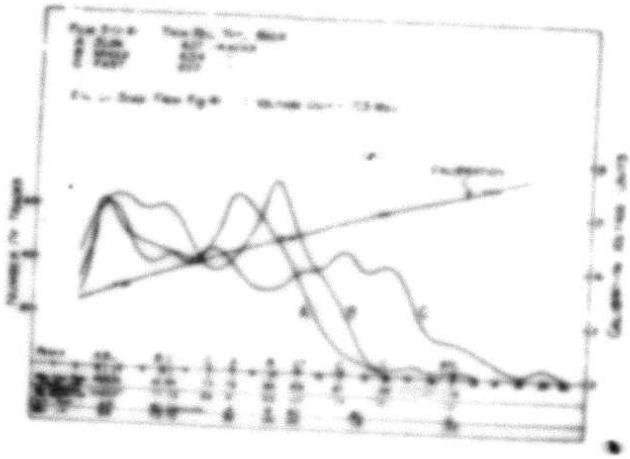


Fig.44--Recoil fragments through back of supporting foil.*

The conversion factor from calibrating voltage to energies of the peaks determined from this factor (17.3 Mev. per voltage unit) are shown at the bottom of the figure. These are much less than the corresponding values of Fig.42.

The loss of energy of the fragments in traversing the aluminum foil can be calculated from the cross-sections given by Knipp and Teller if one assumes the relative stopping power of aluminum to air is the same as for alpha-particles.

# # # # # # # #

* Due to an error, Fig.41 is referred to in the drawing.

As an approximation, assume the cross-section for the different fragments, as calculated by Knipp and Teller, is about the same: 2.8×10^{18} Mev.-cm^2. The mass of the aluminum is .17 mg/cm^2, giving 3.8×10^{18} atoms/cm^2. The relative stopping power of aluminum for alpha particles is about 1.4. Multiplication of these factors yields an energy loss of 15 Mev.

Addition of 15 Mev. to the observed peak energies yields values which agree remarkably well with those of Fig. 42. For comparison, the values from Fig. 42 are given in the bottom line of Fig. 44.

Some discrepancy is to be expected since the assumption of a constant cross-section for the different fragments is not strictly correct, the cross-section being smaller for the lighter fragments. However the data does not justify a more refined treatment. The agreement for the slow neutrons is almost exact for both peaks, indicating that the difference in cross-section is not large for these two particles.

It should be pointed out here that the energy assignments for the total ionization in Fig. 43 were made by setting the slow neutron peak at 160 Mev. and using the calibration curve to determine the other peaks. Since the correction for the stopping-power of the aluminum foil is the same for the three curves, it need not be applied.

Kanner and Barshall made similar measurements on both fragments with slow neutrons but determined the

absolute value of the peak from the calibration voltage directly, obtaining 151 Mev. They estimate the energy loss in the aluminum foil to be 8 Mev. The corrected value is thus 159 Mev. This is 2 Mev. less than their measured sum of the individual peaks. The foil used was of nearly the same thickness as the one in the present experiment so should have 15 Mev. stopping power, according to the cross-section calculation. This would lead to an energy 5 Mev. too great. All of these differences border on the limit of the experimental error so can not do more than indicate that the assumed cross-section is probably an upper limit.

(7). Criticism of results. In the interpretation of the effect of neutron energy on the mode of fission, every effort was made to refrain from relying on data which did not occur in every set of bombardments. Due to the over-lapping of the peaks, small irregularities are not to be trusted unless reproducible.

This overlapping is due to the broadness of the peaks which results from three effects: natural breadth, straggling and statistical fluctuations. The natural breadth is accounted for by the spread in the masses observed for each mode of fission in the chemical experiments. The straggling is due to absorption in the uranium itself and in the supporting foil and could be minimized by decreasing these thicknesses. The statistical fluctuations in any one run are quite large and account for diff-

erences in resolution and peak-height in the different figures. The probability that such fluctuations would be reproduced on two successive runs is, however, very small.

In this work, the absolute value of the fragment energy was determined by assuming the smaller slow neutron peak corresponded to 64 Mev. and calculating the energies of the other peaks from the artificial-pulse calibration curve. This was assumed to be the most accurate method since the extrapolation from known alpha-particle energies magnifies any error in locating the pulse size corresponding to the maximum energy of the alpha particles. Runs always included a set of alpha-particle tracks to insure that the relative energies were of the right order. The calculation of the fission energies from the alpha-particle pulses could give results differing by more than 10%, however, depending on the interpretation of the alpha curve, so the use of the established 64 Mev. peak yielded more accurate results.

When argon was used in the chamber, a decrease in pulse size was observed if two similar runs were made several days apart, one run being taken immediately after the chamber was filled and the other after it had been sealed for two or three days. This was observed in spite of every precaution to avoid leaks. It is thought to be due to the gradual release of foreign gases from the walls of the chamber. While the actual amount of foreign gas

must be small, measurements on the mobility of positive ions have shown that a very small impurity of a foreign gas can produce large effects.

These show that the presence of a trace of a foreign gas causes clumping of the ions and a very great decrease in mobility. Besides this, the intense ionization produced by fission particles makes recombination effects large. If a foreign gas having a large recombination coefficient is present, not all the ions formed will be collected.

Effective outgassing of the chamber was not feasible so the chamber was always evacuated, flushed and refilled with argon immediately preceding each bombardment. Tests made by repeating the first run of a bombardment after a few hours and comparing peak positions showed no measuresble decrease in pulse size during this time. The decrease after 24 hours amounts to only 10%.

It is believed that errors in the actual recording and reading of the films is very slight. The consistent reproduction of the corresponding calibration pulses to within 2% of full-scale deflection indicates that the overall error from linear amplifier through to recorded data cannot exceed this. Subjective errors were checked by having three different observers take data.

The establishment of the most probable energies for each mode of fission is subject to checking with smaller thickness of uranium and a larger number of total counts to decrease the straggling. Such experiments are to be

carried out.

(8). Summary of results from fission experiments.

(a). The observed slow neutron peaks agree within the experimental error with those observed by Kanner and Barshall.

(b). When fast Li-D neutrons are used, new peaks are observed at energies which cannot be explained in terms of the added kinetic energy of the neutron.

(c). The new peaks can be accounted for by the assumption of three new modes of fission: binary asymmetrical similar to that of slow neutrons; highly asymmetrical binary, and symmetrical ternary.

(d). The assumption of symmetrical binary fission is confirmed by the chemical analyses of Yasaki. This mode of fission was also found to occur only with fast neutrons in his investigations. Symmetrical binary fission is to be expected with fast neutrons from the theoretical calculations of Bohr and Wheeler and of Present and Knipp.

(e). The highly asymmetrical fission, occuring only with fast neutrons, is also found by Nishina who identified Hg and Bi among fission fragments from Li-D neutron bombardment.

(f). Ternary fission produces elements in the same range as ordinary binary fission so the chemical evidence is not conclusive. The theoretical calculations by Present give a heat of reaction which agrees with that observed.

(g). The stopping-power for fission fragments calculated by Knipp and Teller gives values which agree with the observed loss of energy by fission fragments traversing aluminum foil.

These results must be taken as provisional and subject to further experimental check. In addition to this, a vast number of questions are raised by the assumed explanation of the new peaks which will require further work. It is hoped that the following questions can be investigated:

(a). Determination of the relative cross-sections for the various processes by more accurate experiments and measurements of the relative abundance of slow and fast neutrons incident on the uranium.

(b). Investigation of the variation of stopping-power with residual range of the fission fragments.

(c). Corresponding measurements with thorium to determine if similar new modes of fission can be induced.

VI. Acknowledgements

The author is indebted to many people for advice and assistance in the various phases of this work. First, he should like to express his sincere appreciation to Dr. Karl Lark-Horovitz, director of this research, who suggested the problems and whose advice and guidance made the successful completion possible.

The active assistance of W.A.Miller in most of the work, especially in the construction of the linear amplifier, is most appreciated. Mr. R.E.Holmquist, now at the University of Washington, helped in the construction of the neutron generator. Dr. I.A.Getting, of Harvard University, was of great help in construction of the high-voltage generator, co-operating both by giving technical advice and by the loan of patterns for special castings.

It is not possible to list by name all who have been of help in at least one phase of the work but mention of Messrs. May, Lawler and Hurd, of the department instrument shop, should be made because of their technical advice and careful workmanship in the construction of the apparatus.

Part of the work on the neutron generator was done while the author was a fellow of the Purdue Research Foundation. Construction of some of the apparatus was with the assistance of NYA labor.

VII. References

(A-1) Alvarez, Phys. Rev. 54 609, 1938

(B-1) Baker and Bacher, Phys. Rev. 59, 332, 1941

(B-2) Breit and Wigner, Phys. Rev. 49, 519, 1936

(B-3) Bethe, Rev. Mod. Phys. 9, 115, 1937

(B-4) Bohr and Wheeler, Phys. Rev. 56, 426, 1939

(B-5) Bradbury, et al. Phys. Rev. 52, 1004, 1937

(B-6) Bohr, Phys. Rev. 58, 654, 1940
59, 270, 1941

(B-7) Bonner and Brubaker, Phys. Rev. 48, 742, 1935

(B-8) Beyer and Whittaker, Phys. Rev. 57, 976, 1940

(D-1) Dunning, et al., Phys. Rev. 47, 704, 1935

(D-2) Dunning, R.S.I. 5, 387, 1934

(D-3) Dunning, Fink and Mitchell, Phys. Rev. 48, 265, 1935

(F-1) Fertel, Gibbs, et al., Proc. Roy. Soc. 175, 316,1940

(G-1) Getting and Fiske, Phys. Rev. 56, 1098, 1939

(G-2) Goldhaber, Hill and Szilard, Phys. Rev. 55, 47, 1939

(G-3) Getting and Leighton, R.S.I. 11, 232, 1940

(H-1) Haworth, Manley, Vore and Leubke, Phys. Rev. 57, 1075, 1940

(H-2) Hahn and Strassmann, Naturwiss. 27, 89, 1939

(H-3) Hansen and Webster, R.S.I. 7, 17, 1936

(J-1) Jentschke and Prankl, Akad. der Wiss. in Wien, 148, 18, 1939

(J-2) Johannson, Zeit. fur Phys. 82, 507, 1933

(K-1) Kanner and Barshall, Phys. Rev. 57, 372, 1940

(K-2) Kirkpatrick and Becherley, R.S.I. 7, 24, 1936

(K-3) Knipp and Teller, Phys. Rev. 59, 659, 1941

(L-1) Lamar and Luhr, Phys. Rev. 46, 87, 1934

(L-2) Lamar, Buechner and Van de Graaff, Journ. App. Phys. 12, 132, 1941

(L-3) Lark-Horovitz and Miller, presented at Washington meeting of A.P.S. Paper in process of publication.

(M-1) Meitner and Frisch, Nature 143, 239, 1939

(M-2) Mitchell and Powers, Phys. Rev. 50, 486, 1936

(N-1) Nishina, Yasaki, et al., Nature 144, 547, 1939

(P-1) Present and Knipp, Phys. Rev. 57, 751, 1940

(P-2) Present and Knipp, Phys. Rev. 57, 1189, 1940

(P-3) Present, Phys. Rev. 59, 566, 1941

(R-1) Rasetti, Phys. Rev. 58, 321, 1940

(S-2) Segré and Seaborg, Phys. Rev. 59, 212, 1941

(T-1) Turner, Rev. Mod. Phys. 12, 1, 1940

(T-2) Tuve, Phys. Rev. 48, 241, 1935

(T-3) Thiesson, Phys. Rev. 57, 1076, 1940

(V-1) Von Halvan and Preiswerke, Compt. Rend., 203, July, 1936

(V-2) Van Voorhis, R.S.I. 11, 77, 1940

(Y-1) Yearian, Journ. Chem. Phys. 8, 1940

(Y-2) Yasaki, Inst. of Phys. and Chem. Research, (Tokyo) 37, #980, 457, 1940

(Z-1) Zinn, Phys. Rev. 52, 655 and 919, 1937