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A FAST NEUTRON COUNTER USING SEMICONDUCTOR DIODES AND COINCIDENCE CIRCUITRY

THESIS

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Preface

Semiconductor diodes of a quality and size suitable for use in detecting charged particles are becoming available. These diodes, when biased in the reverse direction, serve as solid state ionization chambers and provide a means of detecting and measuring the energies of charged particles. Dr. Ralph E. Segel, of the Nuclear Physics Group of the Aeronautical Research Laboratory, suggested detecting the two product charged particles associated with a neutron reaction and determining the energy of the neutrons by measuring the pulse heights from the detectors using the known Q value of the reaction.

The detectors used in the problem were obtained commercially and were not analyzed in great detail. Special chambers were designed and constructed for use with the Aeronautical Research Laboratory Van De Graaff. Special electronic equipment was designed and constructed by Mr. John A. Dooley of the Nuclear Physics Group. Construction of the chambers was done by the Institute of Technology Shop.

I wish to acknowledge the debt and express my sincerest gratitude to Dr. Segel, Dr. Esther Sprenkel, Mr. Dooley and Mr. David Breitenbecker for their interest, extended assistance and consideration throughout the investigation.

I also gratefully acknowledge the kindness and cooperation of Dr. William L. Lehmann and Warrant Officer James T. Miskimen of the Physics Department of the Institute of Technology and Mr. Millard W. Wolfe and his group of the Institute Shop.

C. L. Rucker

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Abstract

Silicon solid-state detectors were used in conjunction with coincidence circuitry to detect and measure the energies of charged particles resulting from a $Li^6(n,\alpha)H^3$ reaction. 5.24 Mev neutrons were obtained by bombarding deuterium gas with 2 Mev deuterons from a 2 Mev Van De Graaff. A chamber was designed and constructed permitting the preparation, measurement and the positioning of a Li^6 foil between the two silicon detectors without breaking the vacuum. A resolution of 578 Kev and a counting efficiency of 4×10^{-8} were obtained where efficiency equals $\frac{\text{counting rate}}{\text{Neutron flux}}$.

I. Introduction

The detection of nuclear particles requires some type of interaction with the detector. For charged particles this interaction is through the excitation and ionization produced by the primary particles while for neutrons the detection must come through secondary charged particles produced by neutron interaction with matter. There are several mechanisms by which the interaction with matter takes place. The more useful ones are:

1. Neutron-induced transmutations in which the product particle(s) makes possible the detection. Examples are (n,α), (n,p) and (n,fission).
2. Neutron-induced transmutations which result in radio active product nuclei. The subsequent decay of the radio active nuclei gives information on the neutron flux which induced the radio activity. Activated foils are an example of this technique.
3. Elastic scattering of neutrons in which the recoil particle is charged and is capable of being detected. The most important example being the elastic scattering of a neutron by a proton.

Neutron detection systems consist of the materials required to bring about one of the processes listed above along with means for measuring or indicating the results of the nuclear process (Ref 4:259). The detectors may vary from sophisticated scintillation systems to the activated foils. Some of the detectors are difficult to use, detector efficiencies are generally low, some detectors are flux limited and others are energy limited. Price (Ref 4:258-315) discusses existing neutron detectors and the advantages and

disadvantages of each. It would be desirable to have a counter which would operate predictably over a wide range of neutron energy and flux, provide for immediate data read out, and resolve neutron groups separated by as little as 100 Kev.

Solid-state semiconductor diodes are used as charged particle detectors. Very small currents flow through the diode when biased in the reverse direction unless minority carriers are produced by some extraneous means. It is desirable that this reverse current be kept to a minimum and Mayer (Ref 3:179) reports that silicon diodes have very low reverse currents. Reverse-biased diodes may be considered as small ionization chambers in which incident charged particles deposit their energies through the production of hole-electron pairs (Ref 2:183). The ionization produced within the diode is independent of particle type, and when collected and conducted to external electronic systems are converted to voltage pulses.

Babcock (Ref 1:116-121) utilized a coated semiconductor diode in developing a miniature neutron detector capable of operating over a neutron flux range of 10^4 to 10^{11} neutrons per cm^2 per second.

Silicon p-n junction detectors are discussed in BNL 4662 (Ref 7:9) and it is reported that diffused silicon p-n junction detectors have been made up to $1cm^2$ in area, with depletion layer thickness up to 0.7mm, negligible dead layers, and exhibiting line widths of down to 20 Kev. Such diodes are essentially windowless to even the most highly ionizing particles, are capable of stopping 10 Mev protons and exhibit energy resolutions substantially less than 100 Kev. These detectors are now becoming commercially available.

This report describes an experimental determination of the effectiveness of a certain solid state detector — lithium — solid state detector sandwich through the use of the $Li^6(n,\alpha)H^3$ reaction and coincidence counting. The experiment is as follows:

1. Deuterons accelerated by the Aeronautical Research Laboratory 2 Mev Van De Graaff generator strike a deuterium target producing 5.28 Mev neutrons by the $d(d,n)He^3$ reaction (Q=3.267 Mev).
2. The neutrons strike a Li^6 target foil producing alpha and tritium particles by the $Li^6(n,\alpha)H^3$ reaction in which

$$_0n' + _3Li^6 \longrightarrow _2He^4 + _1H^3 + 4.789 \text{ Mev}$$

with the product nuclei emitted at 180 degrees with respect to each other in the center of mass system. The Li^6 used in preparing the target was obtained from the Oak Ridge National Laboratory.
3. Solid state detectors are placed on opposite sides of the Li^6 foil so that each detector can count but one particle per reaction event. The size of the detectors is $1cm^2$ and their detection efficiency is a function of the target-detector separation distance. Increasing the separation distance decreases the solid angle subtended at the target center by the detector thereby diminishing the probability that emitted particles will strike the detector.

4. The pulses from the two detectors are fed into a fast coincidence counter to reduce background. The two pulses are added to give the total energy of the two particles which equals the kinetic energy of the neutrons and the Q of the $Li^6(n,\alpha)H^3$ reaction. Thus the device is a spectrometer as well as a counter.

5. All runs were normalized to a current integrator.

Design considerations, experimental procedure, results and conclusions are outlined in the following sections of this report.

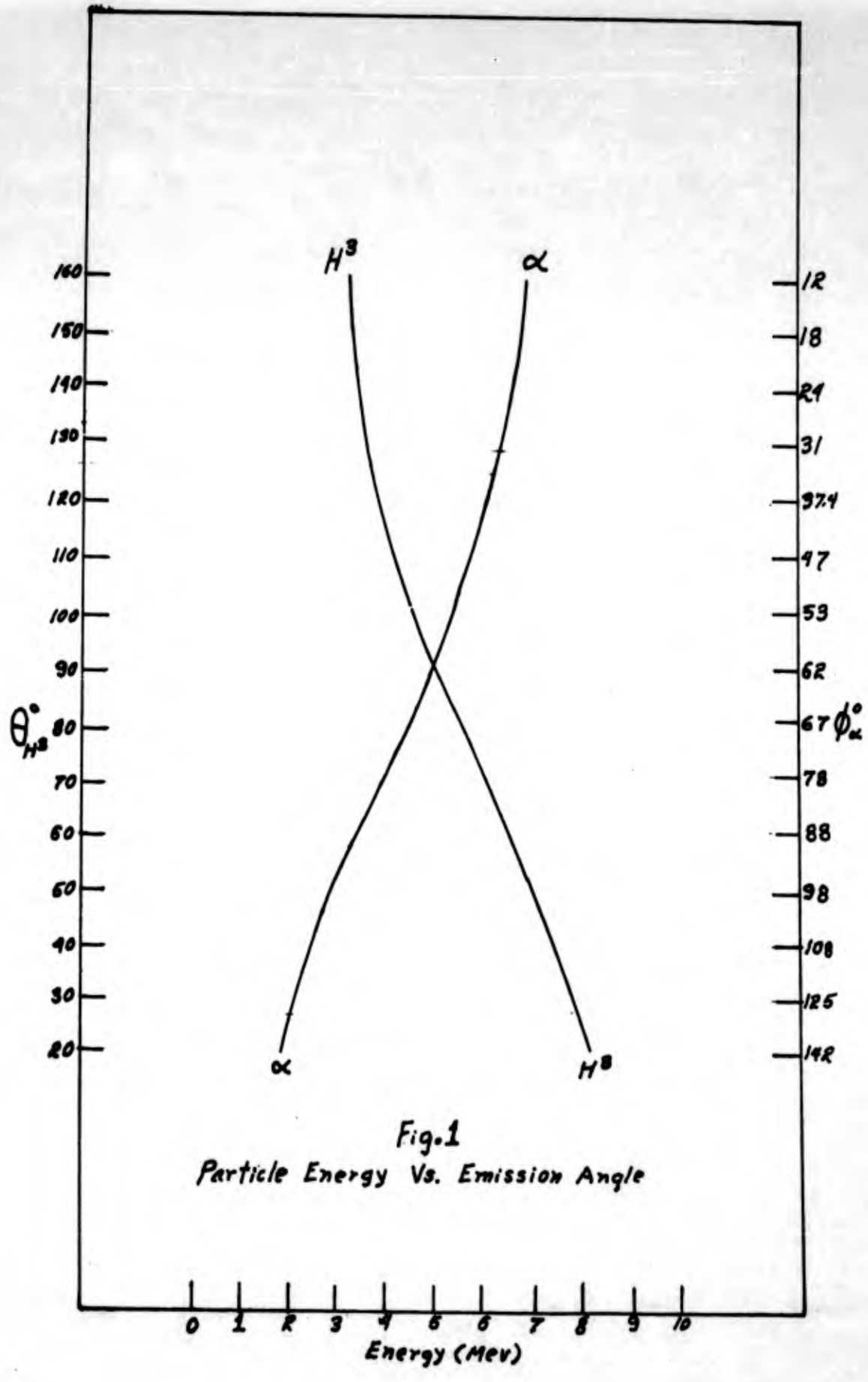


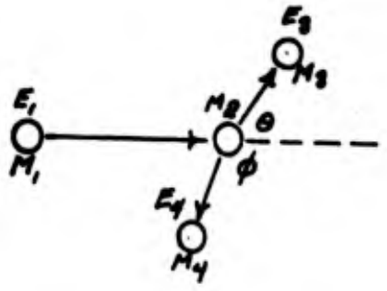
Fig. 1
Particle Energy Vs. Emission Angle

II. Design Consideration

The $Li^6(n,\alpha)H^3$ reaction was used in the experiment primarily because it produces two charged particles. The two-particle production makes possible the use of a double detecting system which, when used in time coincidence, reduces the background.

Product Particle Energy-Angle Relationships

The energies of the ejected alpha and triton are dependent upon the energy of the incident neutron and their angles of emission. Computation of particle energies emission angles are based upon the following (Ref 6:4).



$$Q=(M_1+M_2-M_3-M_4)c^2$$

$$E_T=E_1+Q=E_3+E_4$$

Where:

M_1=mass of incident neutron

M_2=mass of $_3Li^6$

M_3=mass of $_1H^3$

M_4=mass of $_2\alpha^4$

E_T=total energy of the reaction

E_1, E_3 and E_4 are the energies of neutron, H^3 and $_2\alpha^4$ respectively

Solution of these equations yield the results shown in Fig. 1 for energies of $_1H^3$ Vs the angle θ and $_2\alpha^4$ energies Vs ϕ for 5.24 Mev incident neutrons. As one specific example a 5.24 Mev neutron from the $d(d,n)H^3$ reaction yields a tritium particle having an energy of 7.86 Mev at an angle of 30° and an alpha particle with an energy of 2.17 Mev at an angle of 125°. A sample calculation is shown in Appendix A. In general the sum of the angles is a little less than 180°.

Geometric Design Considerations

The functioning of the counter is dependent upon the simultaneous detection of particles produced in the $Li^6(n,\alpha)H^3$ reaction. Because the particles are emitted at approximately 180° to each other the target foil is sandwiched between the two detectors as shown in Fig. 2. In order to obtain the maximum number of coincidence counts the detectors should be as large as possible with a minimum separation distance between the target and detectors. Maximum counting efficiency would thus be obtained. The largest available detectors at this time are $1cm^2$. The separation distances are limited by mechanical design. The foil holder is a brass ring 0.3 cm thick and the foil is attached to one side of the ring. Thus minimum yet equal separation distances are impossible. Clearance tolerances permitting the remote

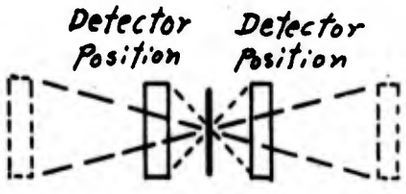


Fig. 2
Detector-Target-Detector Sandwich

positioning of the foil between the detectors plus sufficient clearance for the installation of the detectors in their holders fix the target-detector separation distances at 0.317 and 0.556 cm.

It should be noted that the sum of the alpha and the triton energies depend only on the incident neutron energy and the Q of the reaction. By adding the simultaneous pulses from the two counters the total energy is obtained. The sum of the two energies equals 10.03 Mev for 5.24 Mev neutrons. The total energy less the Q of the reaction equals the energy of the incident neutron.

Neutron Source

Neutrons are required to test the counter system and mono-energetic neutrons are desired. The neutrons are produced by the $d(d,n)He^3$ reaction using 2 Mev deuterons accelerated by a Van De Graaff. Calculations of neutron energy versus emission angle are similar to those used in determining the energies of the charged particles. The Q of the $d(d,n)He^3$ reaction is 3.267 Mev (Ref 6:28) and the energy of the neutron emitted at 5° to the path of the incident deuteron beam is 5.24 Mev. Neutrons are produced along the beam path thus

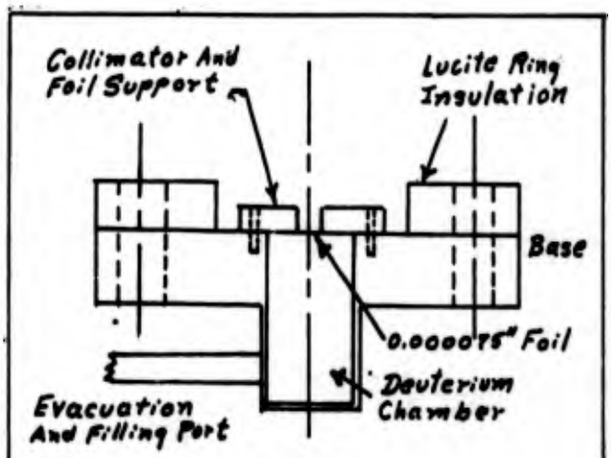


Fig. 3
Deuterium Target Chamber

spreading the effective deuteron energy. In an attempt to hold the energy decrement less than the counter resolution the length of the chamber was selected as 1.6 cm. a distance which gives a 100 Kev energy decrement. This chamber length also allows easy installation of filling and evacuation plumbing. The inside diameter of the chamber is 0.63 cm. The chamber is shown in Fig. 3.

The deuterium is contained within the deuterium target chamber at STP while the chamber is attached to the Van De Graaff beam tube which is maintained at approximately 10 microns of Hg. A vacuum seal is required between the target chamber and the beam tube to contain the deuterium in the chamber. The deuteron beam comes down the beam tube, through a set of 0.317 cm circular collimators, passes through a foil and enters the deuterium chamber where the $d(d,n)He^3$ reaction takes place. The foil must be thin to minimize the loss of deuteron energy in passing through it yet strong enough to withstand the pressure differential and the bombardment by the deuterons. A 0.000075 in nickel foil is used for this purpose. The deuteron energy loss in passing through the foil is 45 Kev.

The deuterium chamber also serves as a Faraday cup. The charge collected by the chamber is summed by the Van De Graaff current integrator. Division of the integrated charge by the charge per deuteron equals the number of deuterons which entered the deuterium chamber. All runs were normalized to the current integrator. The deuterium chamber must be insulated from the beam tube and the evacuation and filling system if it is to serve as a Faraday cup. Lucite insulators and plastic tubing provide this insulation.

The bombarding deuterons may knock electrons from the deuterium chamber walls. If these electrons are not immediately re-collected an incorrect count may be registered by the current integrator. To insure collection of the electrons the deuterium chamber is maintained at a positive potential of 90 volts.

The neutrons used in the experiment are those emitted in the forward direction. To minimize attenuation, the deuterium chamber end wall is made thin (0.158cm). A Chamber-to-chamber distance of 0.024 cm is used.

It is required that the chamber be made of a conducting material if it is to act as a Faraday cup. Since brass satisfies the electrical conductivity requirement and is relatively easy to machine and solder, the chamber is made of this material.

Li^6 Target

The Li^6 target must contain a sufficient number of target nuclei to provide an acceptable number of $Li^6(n,\alpha)H^3$ reaction events yet be sufficiently thin to preclude unacceptable charged particle energy losses in passing through the film. It was determined through preliminary reaction yield calculations and range energy data that a film thickness of approximately 50 μgms per cm^2 would satisfy both requirements with maximum charged particle energy losses of approximately 70 Kev.

The lithium film results from a deposition process and must be supported. The support must have some mechanical strength yet be thin enough to minimize charged particle energy losses in passing through it. A 0.000008 in nickel foil is selected as the best available compromise. Maximum charged particle energy losses in this nickel foil are

less than 100 Kev. Thus the total maximum charged particle energy loss in the film and foil is of the order of 175 Kev.

The target is prepared by the evaporation of lithium onto the nickel foil with the process being accomplished in a vacuum. Exposure of the target to air would result in rapid oxidation. Oxidation of the target film increases thickness and thus adds to absorption of particle energy. The oxygen in the oxide also has a small reaction cross-section for neutron and tritium reactions.

Counter Chamber

To avoid oxidation, the counter chamber (Appendix B Fold-out) must contain a means of target preparation, target thickness measurement and the complete detecting system. Therefore the chamber is composed of three sub-chambers as shown with push rod provision for moving the target foil from the preparation chamber to the film measuring and detection chambers. A brass target ring to which the nickel foil is cemented is screw-attached to the target push rod. The ring has an inner diameter of 1.45 cm and an outer diameter of 1.83 cm. The target passes through rectangular passage ways in its movement from one sub-chamber to another and a remotely operated passageway cover is used to seal the evaporation chamber from the other two during the target preparation phase to prevent Li^6 vapor from contaminating the detectors. Visual examination of the target during its preparation is desired and viewing ports are provided for this purpose. "O" rings seals make the chamber leak proof. The evacuation of the chamber is accomplished through the tube as shown.

The detectors are mounted as near the top cover of the chamber as mechanical limitations permit. This minimizes the distance the neutrons must travel from the deuterium chamber to the Li^6 film thus optimizing the solid angle. The chamber cover is milled to a thickness of 0.158cm in its center area to minimize the cover thickness the neutrons must traverse. The distance from the inner face of the counter cover to the center of the detector is 1.66cm. The chamber body is made of brass.

To evaporate the Li^6 onto the nickel foil an evaporator made of tantulum is attached to a pair of electrodes extending through the bottom cover of the chamber. The lithium is placed in the tantalum container and an electric current passed through the container (commonly called a "boat") causing resistance heating and evaporation of the lithium. It was learned through experience that a 2mm cube of metallic Li^6 provided a target film of approximately 50 μgm per cm^2. It was also learned through experience that the slow evaporation of the Li^6 provided the more evenly deposited films. The size of the tantulum boat is not critical.

An alpha source and a solid state detector are installed in the center or measuring chamber. Foil thicknesses are determined by measuring the energy decrement of the particles in passing through the foil and then determining its thickness from range energy data.

Electronic Equipment

The double-detection technique used in the experiment requires two electronic systems. Equipment designed and built for the experiment is described. Commercially available equipment used in the experiment is listed by

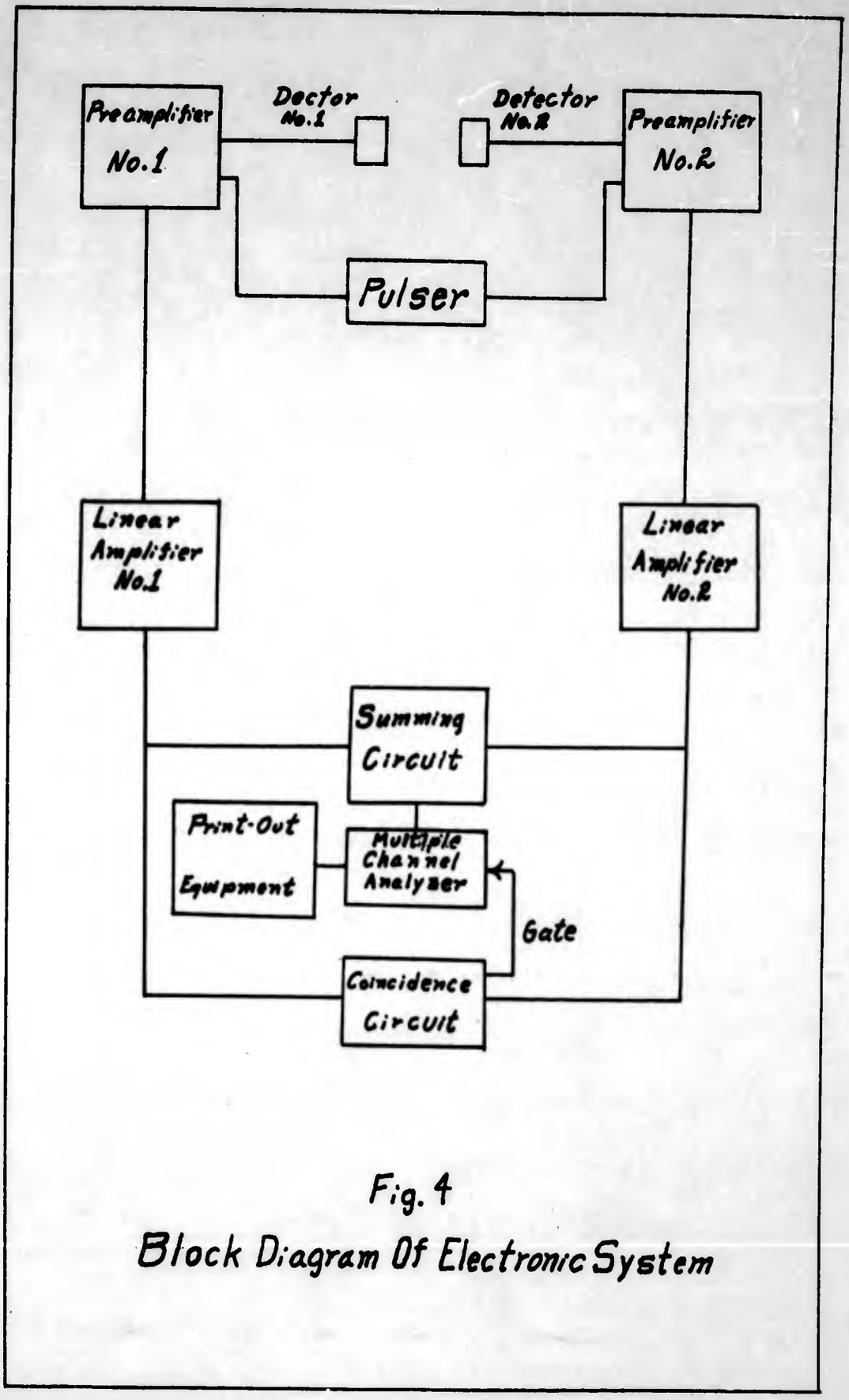


Fig. 4

Block Diagram Of Electronic System

manufacturer and model number only. Fig. 4 shows the schematic arrangement of the electronic equipment.

Preamplifiers. The ionization-produced charge transfer within the detector is of the order of 10^{-13} coulombs. Conventional amplifiers will not accept the small voltages resulting from such charge transfer and linearly amplify them to the degree required therefore, preamplification is required. The preamplifier must be linear, have a fast voltage rise time, have a high signal-to-noise ratio at low voltages and be charge sensitive since the output of the detectors is a charge rather than a voltage. Such an amplifier was designed at Brookhaven National Laboratory for use with solid state diodes. The design of this "Miller Preamplifier" was modified slightly and built for use in this experiment. Voltage rise times of the order of 20×10^{-9} seconds, noise levels equivalent to 40-50 Kev particles and an open-loop gain of 1000 can be obtained with this preamplifier. A schematic of the modified "Miller Preamplifier" is presented in Appendix C. The preamplifiers also supply a very stable and controllable bias voltage to the detectors. Provision is built into the preamplifiers for the acceptance of an externally generated pulse. This feature provides a means of calibration and a source of reference pulses. A preamplifier is required for each detector.

Amplifiers. One amplifier is required for each detector. The amplifiers used are Linear Amplifiers, model Number 101, manufactured by the Cosmic Radiation Laboratories, Incorporated, Patchogue, New York.

Multiple Coincidence. A model 801 Multiple Coincidence Unit manufactured by the Cosmic Radiation Laboratories of Bellport, New York, was used.

Scalers. Models 162 and 134 Scalers manufactured by the Baird Atomic Instrument Company, Incorporated, Cambridge, Massachusetts were used.

Analyzing and Readout Equipment. A model A-262 Converter, a model A-264 display unit, a model A-266 Printer control and a power control panel, serial No. B-34, manufactured by the Radiation Instrument Laboratory, Skokie, Illinois were used.

Detectors. Two one cm square SSR silicon detectors were used. These detectors were manufactured by the Solid State Radiations Corporation, Culver City, California. The detectors are biased at 50 volts negatively.

Pulser. A model M-60 Mercury Pulse Generator, manufactured by the Radiation Instrument Laboratory, Skokie, Illinois was used.

III. Experimental Procedure

The step by step procedure followed in performing the experiment is described in this section. The individual control settings of the electronic equipment are not listed since these values are applicable to the particular equipment used and knowledge thereof would be of no particular value in interpreting the results of the experiment. The operational positions of the deuterium and counter chambers are shown in Fig. 5. The electronics are shown in Fig. 4.

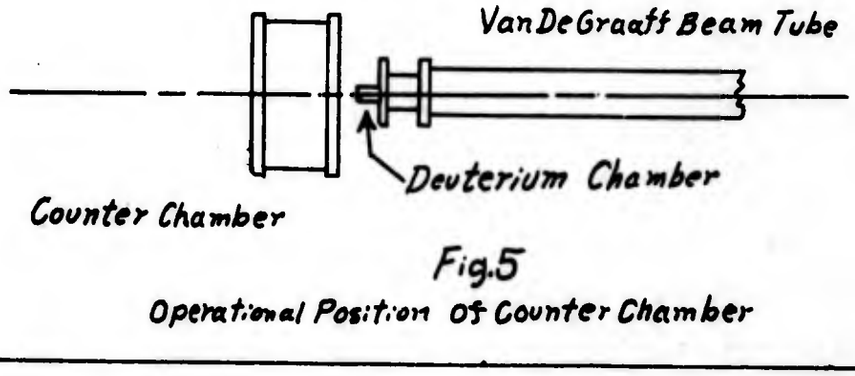


Fig.5
Operational Position of Counter Chamber

Deuterium Chamber

The deuterium chamber is attached to the Van De Graaff beam tube and both the tube and target chamber evacuated. The target chamber is then filled with deuterium to STP. The beam tube is subsequently opened to the Van De Graaff System and the Van De Graaff prepared for operation. The deuterium chamber is placed at

a positive voltage of 90 volts as discussed earlier and connected to the Van De Graaff current integrator by cable.

Counter Chamber

The next procedural step is to prepare the counter chamber and place it in its operating position. A 0.000008 in. nickel foil is cemented to the circular target holder with a resin cement and trimmed to the size of the holder. The holder is then screw-attached to the target control rod and the target positioned within the film measuring chamber with its center aligned between the alpha source and detector C (Appendix B Fold-out). The thickness of the foil is determined from the energy decrement of the alpha particle and range energy curves (Ref. 8). The target is then withdrawn from the measuring chamber and positioned with its center over the center of the tantalum boat with the foil side nearest the boat and parallel to it. The positioning is quite important since an even deposition of Li^6 over the surface of the foil is required. The evaporating boat is charged with a carefully cleaned cube of Li^6 approximately 2mm on a side. The target control rod is then locked in position with the set screw. The chamber is then closed and the passageway between the measuring and evaporating chamber closed and locked in position and the chamber evacuated to approximately 70 microns of mercury. The evacuation valve is then closed and the chamber removed to a D. C. power source and the electrodes leading to the boat connected to the source of power. Evaporation is accomplished at approximately 12 amperes at 2 volts for 30 seconds. Upon completion of the evaporation the chamber is removed and returned to the

vacuum system. The chamber passageway is then opened and the lithium target positioned within the film measuring chamber and the thickness of the nickel foil plus film is determined as before. The difference between the two thicknesses is the thickness of the lithium film and this thickness is used in calculating the number of lithium atoms contained in the target. Upon completion of the film measurement the target is inserted into the detector chamber and positioned between detectors A and B (Appendix B). The detector positions are fixed and, since the foil is cemented to a ring shaped holder of finite thickness the detector to foil distances are unequal with the foil to detector number one distance being 0.317cm and the foil to detector number two distance being 0.556cm. Detector design limits the center line distance of the target and detectors to 1.628cm from the inside of the chamber cover. This distance plus the cover thickness of 0.158cm make the distance from the top plate of the chamber to target center 1.786cm. The chamber is then placed in a supporting mount and positioned facing the deuterium target chamber, center-to-center with it and at a separation distance of 0.024cm (Fig. 5).

Electronics

The detectors are separately connected to preamplifiers and biased at 50 volts negatively as recommended by the manufacturer. The preamplifiers are connected through secondary linear amplifiers to the multiple coincidence and summing circuits and then to the counting devices (Fig. 4). In the experiment an additional routing from the coincidence circuit to a monitoring oscilliscope was used.

The Van De Graaff is then placed in operation at a beam current of approximately 3.3 micro-amperes with a beam or deuteron energy of 2 Mev. The deuterons accelerated by the Van De Graaff stream down the beam tube through 0.317 cm circular collimators and into the deuterium chambers where they react with the deuterium in the $d(d,n)He^3$ reaction. The neutrons which are emitted in the forward direction enter the counter chamber at a rate of 3.49×10^6 neutrons per steradian per current integrator count.

The detector pulses resulting from the production of charged particles in the $Li^6(n,\alpha)H^3$ reaction which are subsequently detected are preamplified, then amplified and fed into the summing and coincidence circuit as shown in Fig. 4. The summing circuit operates continuously, but the coincidence circuit acts as a gate which permits only the sums of coincidence pulses to enter the multi-channel analyzer. The multi-channel analyzer then energy sorts the pulses and feeds this data into the print-out equipment. The data is printed out in terms of coincidence counts per channel. The electronic equipment had been calibrated with an alpha source therefore the energy represented by each channel is known.

IV. Results

The geometry of the system affects yield calculations and the following simplifying assumptions are made:

1. The center of the deuterium is the point source of the neutrons.
2. The effective area of the target equals the area of each detector.
3. Each target atom sees the same neutron flux, i.e., there is no neutron absorption by the target.
4. All reactions occurring in the foil may be treated as though they took place at the center of the foil.
5. The emission of the charged particles is isotropic.

No quantitative calculation of the errors introduced by these assumptions were made. Only qualitative and geometrical arguments were used.

Yield Calculation

The distance from the center of the deuterium chamber to the target center is 2.72cm and the cross-section for the $Li^6(n,\alpha)H^3$ reaction is $79.5 \times 10^{-27} cm^2$ (Ref. 5). The number of 5.28 Mev neutrons emitted in the forward direction per current integrator count is 3.49×10^6. A 62.5 $\mu gm/cm^2 Li^6$ film contains 6.27×10^{18} atoms in the $1 cm^2$ target. The number of reactions taking place in the target per current integrator count then is given by

$$\frac{(79.5 \times 10^{-27} cm^2 \times 4\pi)(6.27 \times 10^{18} \text{atoms})(3.49 \times 10^6 N')}{4\pi (2.72 cm)^2} \quad \frac{}{(\text{Steradian})(\text{Current Integrator Count})}$$

$$= 0.236 \text{ reactions per current integrator count.}$$

Fig. 1
Plot of Coincidence Counts vs. Channel No. And Neutron Energy

The collection efficiency of the detector system is next computed. The detector-target geometry is shown in Fig. 6. From the data displayed in Fig. 1 it can be seen that if one of the reaction particles terminates in the more distant detector, the second particle must terminate in the other detector. However the converse of this is not true. Consequently the collection efficiency of the more distant detector becomes that of the entire system. The collection efficiency of this detector for one particle is the solid angle subtended by the detector at the target center divided by 4π. Since there are two particles the collection efficiency will be doubled. The solid angle ratio is 0.144 and the detection efficiency is 0.288.

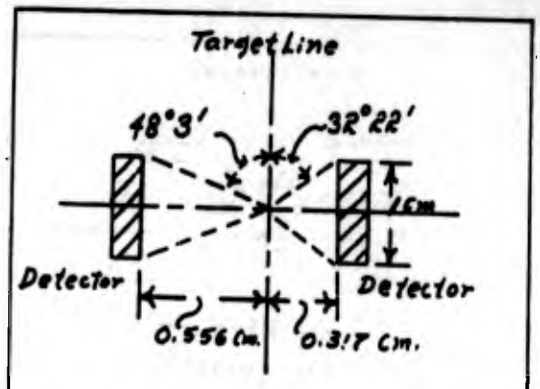


Fig. 6

Detector-Target Geometry

The yield or calculated number of coincidences per current integrator count then equals the product of the detection efficiency and the number of reactions taking place in the target per current integrator count. Using the values above, 68 coincidences should be observed for every 1000 counts registered by the current integrator.

Experimental Data

The coincidence counts versus analyzer channel and incident neutron energies are plotted in Fig. 7. The counter was exposed to a number of neutrons corresponding to 18,500 current integrator counts and a total of 757 coincidences were observed.

Interpretation of the Experimental Data

Three coincidence peaks appear in the data whereas calculated data would predict the appearance of a single, well defined peak at or near the 5.24 Mev energy level. The peak appearing near zero neutron energy results from thermal neutron reactions. In the production of neutrons for the experiment some of those produced eventually become thermalized and are scattered into the chamber. While the number scattered into the target may be quite small, the cross-section for the thermal neutron - Li^6 reaction is of the order of 1000 barns as compared to a cross-section of 0.0795 barns for 5.24 Mev neutrons. Therefore, a small number of thermal neutrons produce relatively large numbers of reactions. A second peak is observed at a neutron energy of 1.3 Mev. This peak is believed to result from contamination, possibly carbon, resulting from the bombardment of lubricants with charged particles. The reaction between 2 Mev deutrons and carbon produces neutrons with energies approximately equal to those observed in the second peak.

The peak appearing near the 5.24 Mev energy level is the anticipated peak. The peak tapers off on its low energy side rather than falling sharply to zero as it does on the high energy side of the peak. It was known that the detector facing the back or nickel side of the lithium target was of low resistivity and since the thickness of the depletion layer of a semiconductor diode varies as the square root of its resistivity it had a thin depletion region. While the range of the alpha particles in the diode material is such that even the most energetic deposit all of their energy within this thin depletion layer, the range of the tritium particles in the diode exceeds the thickness of the reduced

depletion region. Therefore, not all of the energy of the more energetic tritium particles may be deposited in the detector, the amount of energy deposition varying with the angle of entry of the tritium particles into the detector. The sloping of the peak on the low energy side is attributed to this factor.

The total energy of a $Li^6(n,\alpha)H^3$ reaction with 5.24 Mev neutrons is 10.03 Mev and this amount of energy would be deposited within the two detectors if there were no loss of energy by the particles in passing through the lithium film and nickel target foil and if both detectors had depletion regions of such thickness that energy deposition within them was complete. Since the energy decrement with range is greater for alpha particles than for the tritium the maximum total energy deposited should occur when a maximum energy alpha particle is emitted from the surface of the lithium and the tritium particle passes through the lithium and nickel and on to the detector. The angle of emission of the tritium particle is 124^o and that of the alpha is 32^o22^1 which is the minimum angle for alphas to strike the detector. The energy of the triton is 3.51 Mev and the alpha has a 6.52 Mev energy. The triton must pass through 2.09×10^{04} cm of lithium and 3.63×10^{-5} cm of nickel. The energy loss by the tritium in the lithium is 0.055 Mev and 0.001 Mev in the nickel for a total energy loss of 0.0561 Mev. The maximum amount of energy deposited then equals 9.97 Mev. This is the maximum energy observed in Fig. 7.

The resolution of the counter is the width of the coincidence peak at one half peak height expressed in electron volts. This width is 578 Kev.

The point of delineation between the predicted peak and the peak attributed to contamination is taken to be 7.14 Mev. The number of coincidences above this energy level are then interpreted to be those resulting from interaction between the lithium and the 5.24 Mev neutrons. The number of coincidences in this energy range is 313. The predicted number for 18,500 counts is the product of the computed coincidences per count ratio (0.068) and the total number of current integrator counts. This predicted product of 1258 counts is approximately four times the number observed.

Analysis of Discrepancy

The energy of the deuterons after having passed through the 0.000075" nickel foil was assumed to be 2 Mev. The loss of energy in passing through the foil was 0.045 Mev. The corrected energy of neutrons produced was 5.23 Mev rather than 5.24 Mev. The difference in cross-section for these two energies is indiscernible from cross-section data available. The total energy of the reaction then equals 10.02. rather than 10.03 Mev. The number of reactions is unaffected and the energies presented in Fig. 7 are larger by 0.2% than recomputed particle energies resulting from the lower neutron energy. The effects of deuteron energy losses in passing through the nickel on the number of coincidences is then negligible.

The experiment was conducted with a 3.3 micro-amp deuteron current and the deuteron chamber foils suffered leak producing damage allowing deuterium to escape from the chamber. The overall counting period was divided into shorter periods and the deuterium replaced between periods. Loss of deuterium does not affect current integrator counts but

does lower the number of neutrons produced through a decrease in the number of deuterium atoms available for neutron producing interaction. The counting periods were unequal due to one case of excessive foil damage. The weighted effect of leakage is estimated to have been a loss of 36 of the coincidences. Correcting for pressure losses increases the number observed to 349 coincidences and ratio of number predicted to the number observed becomes 3.6.

The efficiency of the counter is then 4×10^{-8} where efficiency is defined as

$$E = \frac{\text{observed counting rate (counts per current integrator count)}}{\text{neutron flux } ({}_0n^1 \text{ per cm}^2 \text{ per current integrator count})}$$

and the neutron flux is the flux at target center.

Target measurement is one possible source of error in that the lithium film was presumed to be uniformly thick although it could be measured only at its center. It was also necessary to make an interpolation of range energy data in computing the target thickness.

Considering the crudeness of the yield calculation the discrepancy between the calculated and experimental yield is not considered serious.

1. The geometry is optimistic because the center of the target is the most favorable position for the emission of particles resulting in simultaneous detections. Therefore the assumption that all reactions take place in the center of the target could cause the calculated number of coincidence counts to be in error by as much

as a factor of 2 (Ref private communication with Dr. John W. Olness).

2. It is estimated that the assumption of isotropic emission of particles introduces an error of 20%.

V. Conclusions

The purpose of the experiment was to investigate the feasibility of a fast neutron counter using semi-conductor detectors and coincidence counting. The results of the experiment prove that such a counter is feasible. Film deposition was a problem in the experiment and an improved technique in target preparation is necessary to assure uniformly thick targets at the thickness desired. Fifty microgram per cm^2 appears to be a practical thickness.

Detailed energy resolution studies were beyond the scope of the experiment. The measured resolution was 578 Kev. Even though no particular effort was made to optimize the energy resolution of the counter, resolution observed compares favorably with that of existing counters.

It may be possible to improve the energy resolution of the counter through refinement of the associated electronic system. Detrimental effects attributable to the detectors can be minimized through the careful selection of detectors.

The counter exhibits promise as a spectrometer and this area merits further investigation.

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Appendix A

Particle Energy Determination

Define:

$$A_{14}=\frac{M_1 M_4 (E_1/E_T)}{(M_1+M_2)(M_3+M_4)} \qquad A_{23}=\frac{M_2 M_3}{(M_1+M_2)(M_3+M_4)}\left[1+\frac{M_1}{M_2}\frac{Q}{E_T}\right]$$

$$A_{13}=\frac{M_1 M_3 (E_1/E_T)}{(M_1+M_2)(M_3+M_4)} \qquad A_{24}=\frac{M_2 M_4}{(M_1+M_2)(M_3+M_4)}\left[1+\frac{M_1}{M_2}\frac{Q}{E_T}\right]$$

Then:

The laboratory energy of the light particle is given by:

$$E_3=E_T A_{13}\left[\cos\theta + (A_{24}/A_{13} - \sin^2\theta)^{\frac{1}{2}}\right]^2$$

The laboratory energy of the heavy particle is given by:

$$E_4=E_T A_{14}\left[\cos\phi + (A_{23}/A_{14} - \sin^2\phi)^{\frac{1}{2}}\right]^2$$

The laboratory angle of the heavy product is given by:

$$\sin\phi=\left(\frac{M_3 E_3}{M_4 E_4}\right)^{\frac{1}{2}}\sin\theta$$

Sample calculation to determine the energy of the tritium particle emitted at 60° by the interaction of a 5.24 Mev neutron with Li^6.

$M_1=1, M_2=6, M_3=3, M_4=4, E_1=5.24$

$Q=4.789$ Mev and $E_T=10.03$ Mev

$$A_{13}=\frac{(1)(3)}{(1+6)(3+4)}\left[\frac{5.24}{10.03}\right]=0.0312 \qquad A_{24}=\frac{(6)(4)}{(1+6)(3+4)}\left(1+\frac{1}{6}\,\frac{4.789}{10.03}\right)=0.528$$

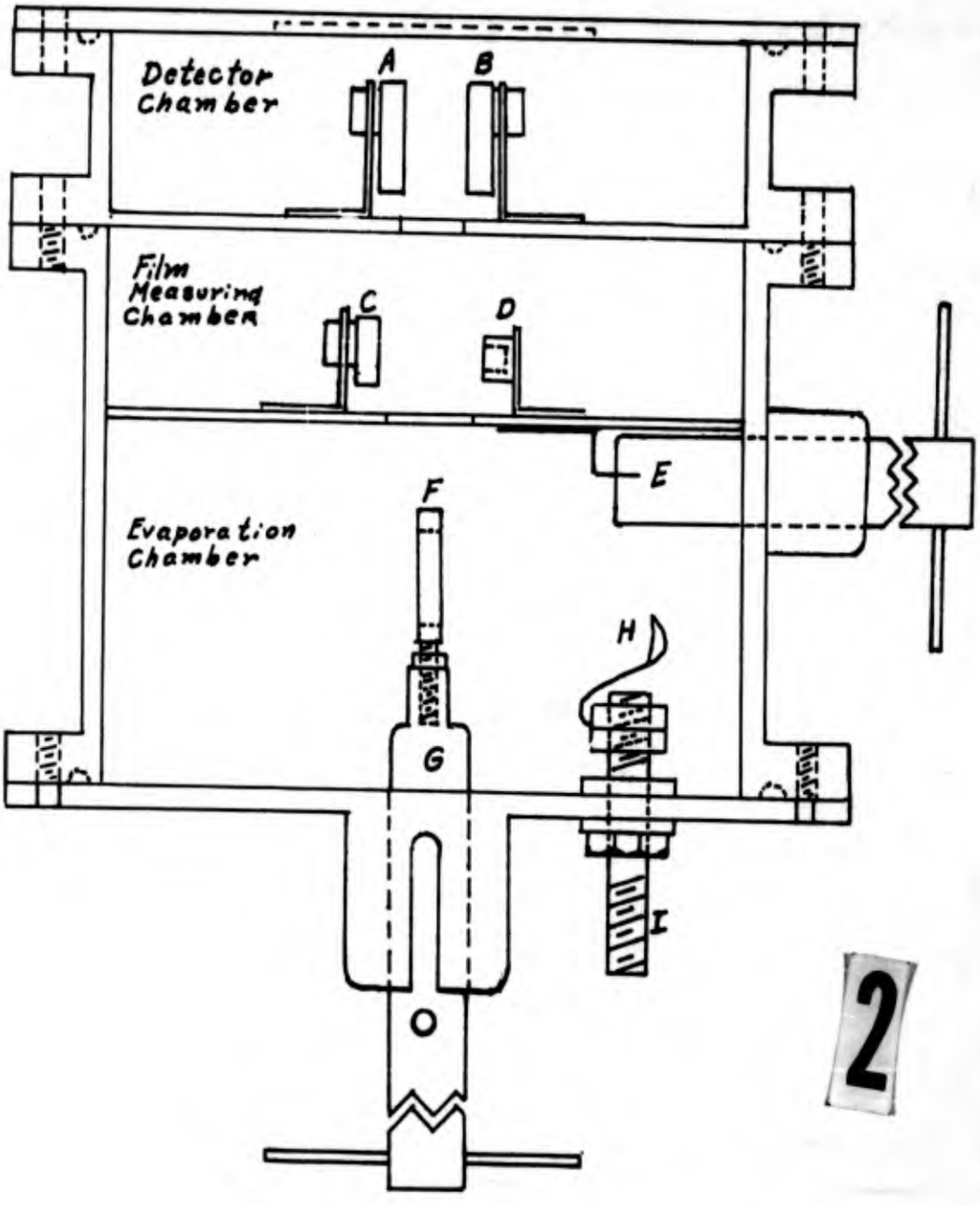
$$E_3=(10.03)(0.0312)\left[0.5+(16.9-0.75)^{\frac{1}{2}}\right]^2$$

$E_3=6.56$ Mev

Appendix B

Counter Chamber

A and B - Solid State Diodes (1 Cm.²)
C - Solid State Diode
D - Alpha Source Holder
E - Passage Cover And Actuating Rod
F - Target Holder Ring
G - Target Control Rod
H - Tantalum Evaporation Boat
I - Electrodes



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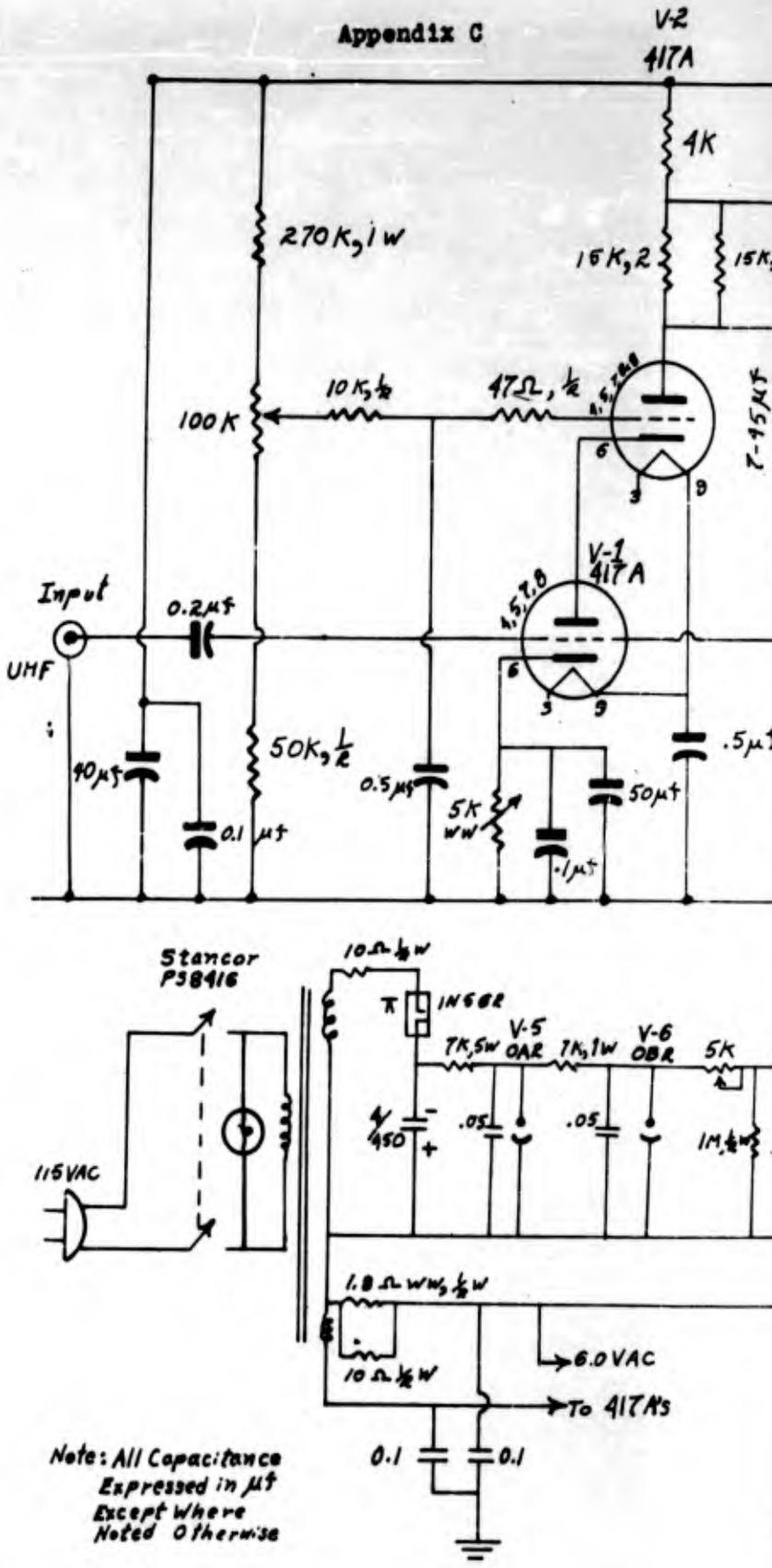
Counter Chamber

Scale 1"=1"

Appendix C



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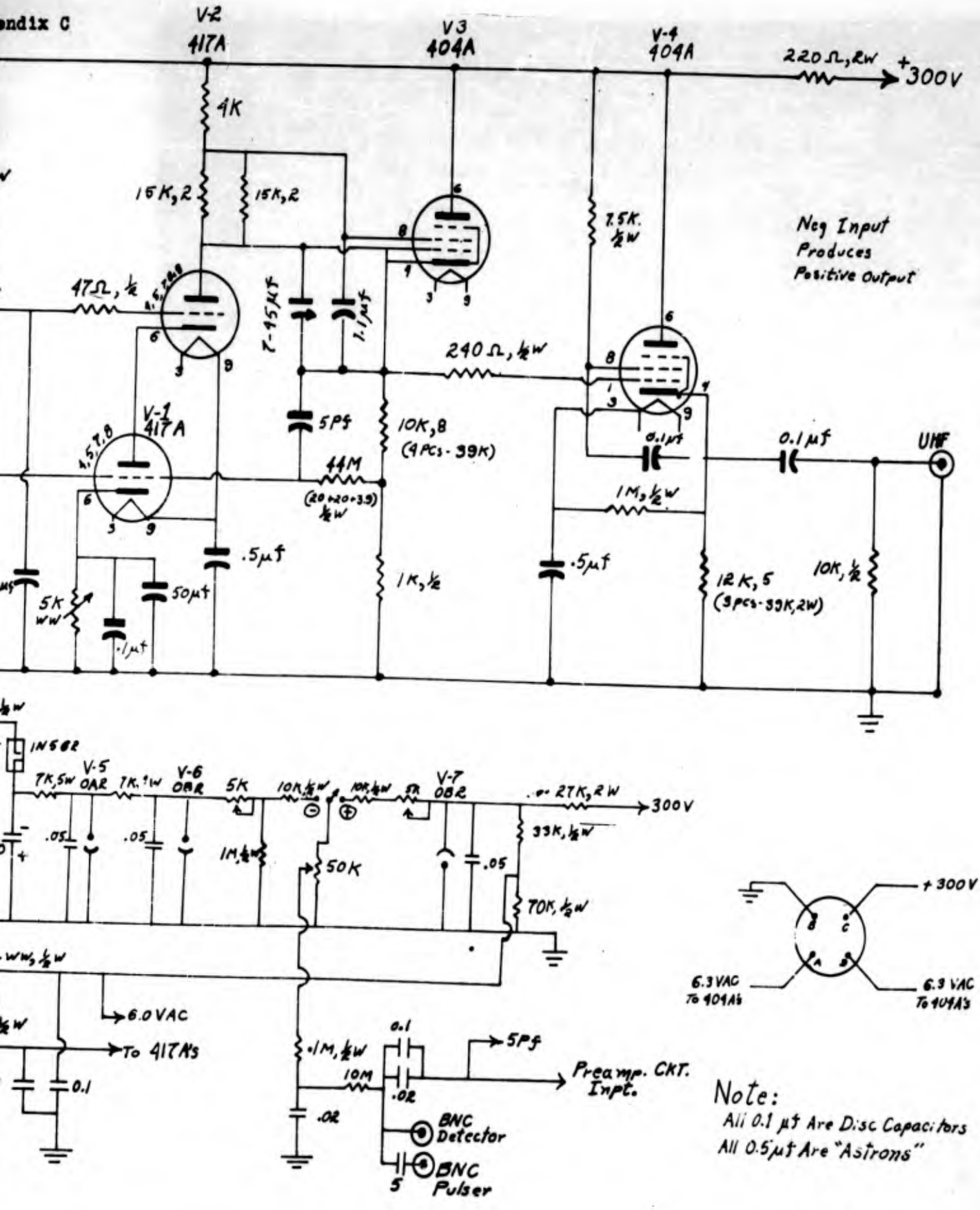

Note:
All 0.1 μf Are Disc Capacitors
All 0.5μf Are "Astrons"

PREAMPLIFIER SCHEMATIC

2

GE-NE/Phys/61-16

Vita

Carl L[redacted] Rucker was born on [redacted] in [redacted], the son of Carry Rucker and Grace [redacted] Rucker. He was graduated from the [redacted] Institute of Technology with the degree of Bachelor of Science in Physics in June 1942. He served in the U. S. Army Air Corps as an aviation cadet and officer from 1942 to 1945. Subsequently he was graduated from Marshall College with the degree of Master of Arts in Educational Administration and Geography and recalled to active duty with the USAF in 1950. His most recent military assignments prior to coming to the Institute of Technology were with the Air Defense Command and the Military Assistance Advisory Group Taiwan.

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This thesis was typed by Mrs. Marjorie Felton.

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