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THE TOTAL NEUTRON CROSS-SECTION OF COBALT, MANGANESE AND MOLYBDENUM

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TABLE OF CONTENTS

INTRODUCTION Page 1

PART I EXPERIMENTAL EQUIPMENT

I-a Argonne Electrostatic Accelerator

1. Introduction 3
2. Description of the Van de Graaff 3
3. Energy Control of the Van de Graaff 4
4. Proton Beam and Rotating Target 7

I-b Construction of Neutron Counter Tubes

1. Introduction 9
2. Required Characteristics 9
3. Mechanism in the Counting Tube 10
4. Design Calculations 12
5. Counter Operating Characteristics 14
6. Counter Assemblies 16
7. Resolution Time of the Counting System 17

I-c Calibration of Counters

1. Introduction 19
2. Electrical Arrangement 19
3. Extraneous Counts 20
4. Linear Amplifier 21
5. Gamma-ray Sensitivity 22
6. Periodic Check of Counting Sensitivity 23

I-d Lithium(p,n)Berylium Reaction

1. Introduction 24
2. Li(p,n)Be Reaction 25
3. Measurement of Target Thickness 28
4. Monitoring the Neutrons 31
5. 10 per cent Yield of Neutrons 32

PART II MEASUREMENT OF THE TOTAL NEUTRON CROSS-SECTION OF COBALT AND MANGANESE AND OTHERS

II-a Introduction to the Measurements

1. Reasons for the Measurements 34
2. Transmission Measurements 35

TABLE OF CONTENTS CONTINUED

3. Compilation of Neutron Cross-Sections 37

II-b Initial Group of Elements

1. Choice of the Elements 39
2. Exclusion of Scandium 40
3. Physical Characteristics of the Samples 40

II-c Arrangement of the Target, Sample and Detector

1. Experimental Requirements 43

II-d Precision of the Measurements

1. Variations in Energy 45
2. Statistical Errors 47
3. Errors in the Monitor 51
4. Errors in the Cross-section 53

II-e Measurement of the Background

1. Nature of the Neutron Background 57
2. Measurement of the Background 58
3. Variations in the Background 60

II-f Scattering-in Correction

1. Meaning of Scattering-in 62
2. Calculation of the Scattering-in Correction 62
3. The Magnitude of the Scattering-in Correction 64

II-g Initial Results

1. Range of the Data 66
2. Value of the Data 67
3. Total Neutron Cross-section of Vanadium 67
4. Total Neutron Cross-section of Columbium 68
5. Total Neutron Cross-section of Cerium 68

TABLE OF CONTENTS CONTINUED

II-h Final Results

1. Measuring the Detailed Cross-section 69
2. The Total Neutron Cross-section of Manganese 69
3. The Total Neutron Cross-section of Cobalt 70
4. Agreement with Vanadium 70
5. Resolution of Structure 71
6. Failure to Observe the 10 per cent Yield of Neutrons 72

PART III MEASUREMENT OF THE TOTAL NEUTRON CROSS-SECTION OF MOLYBDENUM

III-a Introduction

1. Reasons for Measuring Molybdenum 73
2. Difference Between This and the Earlier Measurements 74

III-b Description of the Detector

1. Description of the Counter Arrangement 75
2. Purpose of the Detector 75
3. Scattering-in 76
4. Use of the Monitor 77
5. Difficulties with the Counters 78
6. Back Angle Work 78
7. Measurement of Background 79
8. Additional Considerations 79

III-c Molybdenum Sample Characteristics

1. Density and Purity 81
2. Characteristics of the Molybdenum Sample 81

III-d Accuracy of the Measurements of Molybdenum

1. Energy Variations 83
2. Failure to Observe Structure 83
3. Cross-section Dependence on Sample Thickness 84

TABLE OF CONTENTS CONTINUED

III-e Final Results on Molybdenum

1. The Total Neutron Cross-section for Molybdenum Page 85

CONCLUSIONS

1. Dependence of Fast Neutron Cross-section on Mass Number 86
2. Cross-section Dependence on Mass Number at Particular Energies 87

REFERENCES

APPENDIX: Total Neutron Cross-sections of Cobalt, Manganese and Molybdenum. (Paper presented to Editor of the Physical Review for publication.)

INTRODUCTION

This thesis consists of the original work using the Argonne National Laboratory Electrostatic Generator. Measurements of this type were suitable for the initial use of the machine.

The thesis work was done during a year leave of absence from the faculty of the University of Cincinnati during the school year 1948-49 and short periods since. The author was employed as a physicist in the Van de Graaff Group of the Experimental Nuclear Physics Division of the Argonne National Laboratory.

It is advisable to divide this presentation into three distinct sections which the phases of the work suggest. The initial phase consisted of completing the electrostatic accelerator and the associated equipment required to do this work and other work planned for the Van de Graaff. The salient points of the construction program will be set forth for the following reasons.

(a) The design and construction of several pieces of equipment were undertaken as a part of this thesis.

(b) The techniques of operation and measurements with a Van de Graaff indicate its range and limits.

(c) The nature of the neutrons obtained from the Van de Graaff bears directly upon the accuracy and techniques of the measurements.

The second phase of the work is the measurement of the total neutron cross-sections of several elements using a single neutron counter with a limited amount of shielding. The reasons for these measurements, the techniques, and the results are given.

The third phase is the measurement of the total neutron cross-section of molybdenum using a group of shielded counters. This technique is different from that of part two. The reasons for these measurements, the techniques, and the results are given.

Lastly the nature of the total neutron cross-sections of many elements is discussed and the results of this work are compared to the general picture.

PART I EXPERIMENTAL EQUIPMENT

I - a Argonne Electrostatic Accelerator

1. Introduction

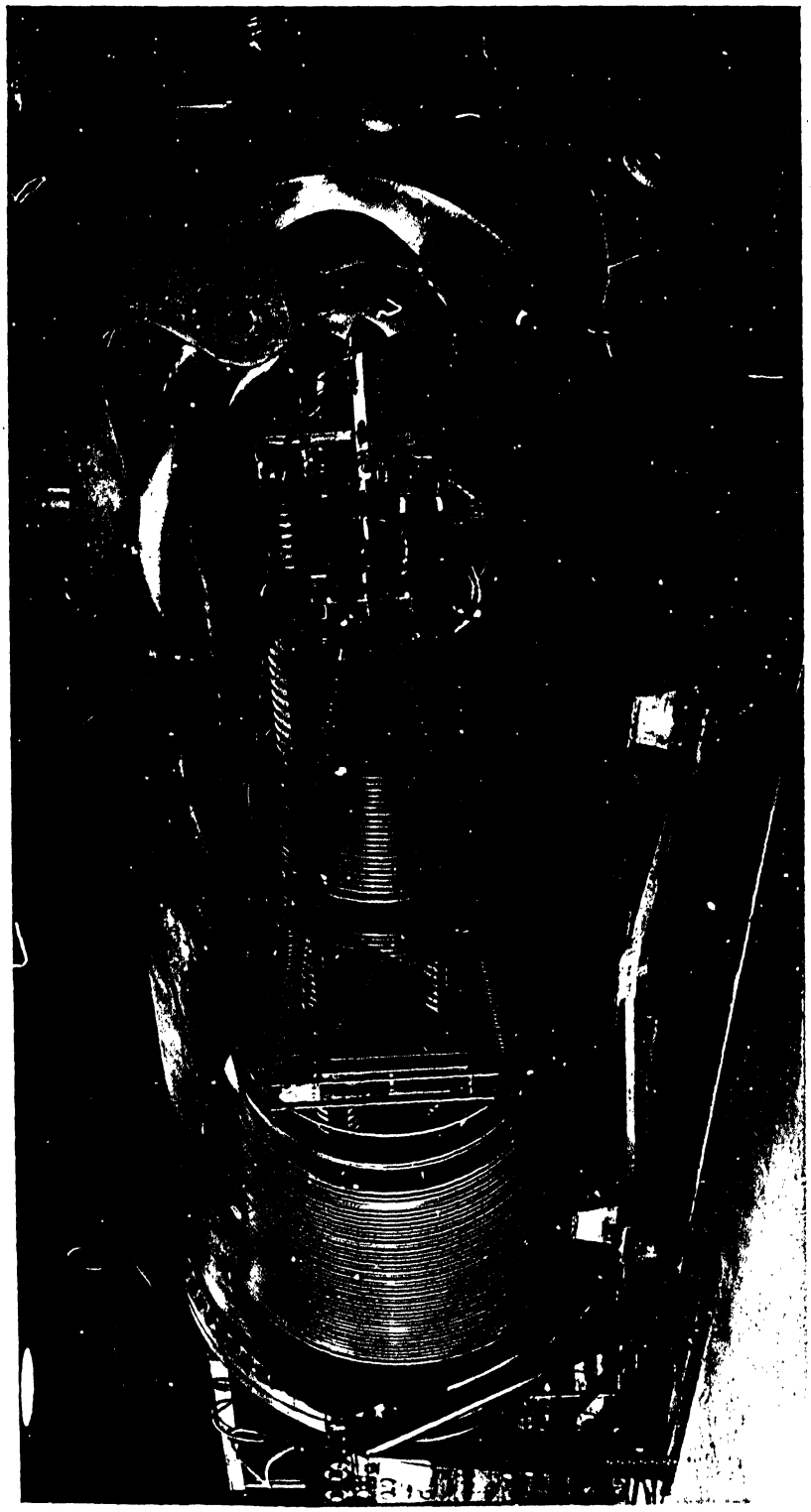
The Argonne National Laboratory built their Van de Graaff to provide facilities for the Experimental Nuclear Physics Division to measure nuclear properties, reaction thresholds, scattering of particles, etc.

The Van de Graaff is an outstanding instrument due to its high energy resolution and versatility in accelerating various types of particles, also due to its wide range of neutron energy production.[1]

The operating principle is simple but the number of components required to complete the machine is large and precludes the early use of the machine. The photograph of the completed machine is ample proof of the complexity of the instrument. This photograph is Fig. 1.

2. Description of the Van de Graaff Accelerator

The construction of an electrostatic accelerator was begun by the Argonne National Laboratory in 1946 under the direction of Dr. Roland Perry.[2] The accelerator was patterned after those at the University of Wisconsin[3] and thus is pressurized. It is planned that the machine have a top energy of six million volts and all the accessories are designed to allow operation to that voltage.



The initial use of the machine for nuclear measurements was in August 1949 when the initial cross-section measurements of this thesis were started.

The Van de Graaff is illustrated by the drawing, Fig. 2, and operates in the well known fashion[4] of this type of accelerator. This particular machine has the following unique features:

(a) The horizontal construction of the machine permits rolling away the outer tank and the shells giving convenient access to the inner components of the accelerator.

(b) A Zinn type ion source.[5]

(c) Two accelerating tubes which permit differential pumping and make available an additional vacuum tube for experimental use.[6]

(d) A pair of analyzers which permit rapid switching from one experimental setup to another.

(e) A variable corona system for most advantageous distribution of the voltage through the machine.

Fig. 1 shows the complexity of the machine and the use of guard rings and corona needles and plates to obtain a large voltage gradient and an optimum accelerating field.

3. Energy Control of the Van de Graaff

The control of the accelerating voltage of the machine, and thus the energy of the beam, was accomplished by the use of an electrostatic analyser[7] which deflects

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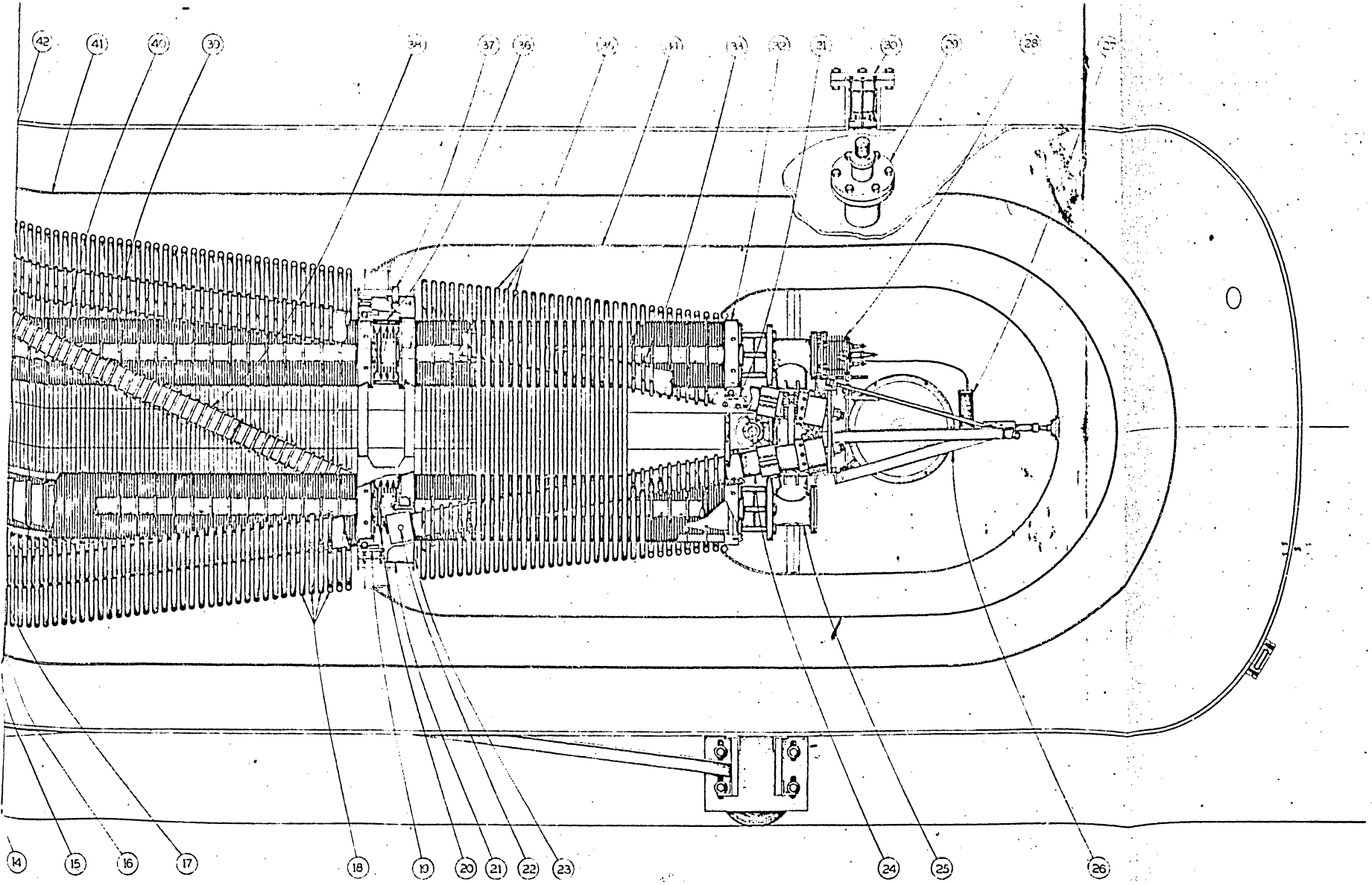


ARGONNE NATIONAL LABORATORY

1 MEV ELECTROSTATIC GENERATOR

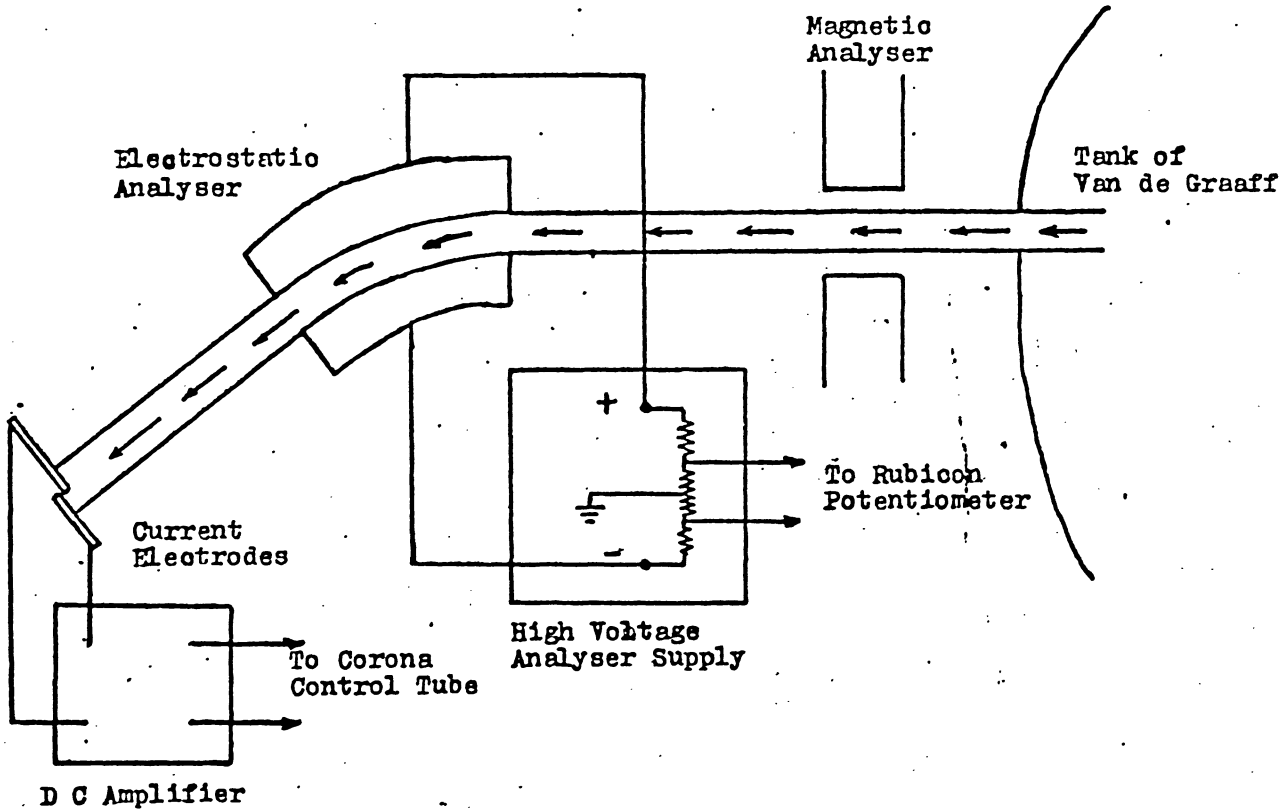
the HH^+ beam, i.e., the hydrogen ion beam. The ions are separated from the total beam by a magnetic analyser. The neutrons were produced by the Li(p,n)Be reaction.[8] Thus, only the acceleration of hydrogen gas was involved. The H^+, or proton, was deflected by the magnetic analyser so as to fall down the target tube.

Since the control of energy is of such importance in all work, a great amount of effort was directed towards precise control. Fig. 3 illustrates the system of energy control using the electrostatic analyser and the associated equipment. The establishment of an accelerating potential and its control is initially dependent upon the charging rate, i.e., the belt current. Secondly, it is dependent upon the loss of charge down the insulators, the corona system and across the gaps between shells. Thirdly, it depends on the conduction of charge down the accelerating tube by the beam and up the tube by the waste current.

The waste current is secondary electrons caused by the beam hitting residual gas in the accelerating tube, of the defining slits, and the electrons purposely introduced by a control element. These electrons produce high energy X-rays whose maximum energy is the operating energy of the machine. Special precautions must be taken to avoid exposing the researchers to these X-rays.

The beam passes down the accelerating tube and then

Figure 3 Voltage Control System



is deflected and separated by the magnetic analyser. The ion beam proceeds into the electrostatic analyser. It is deflected by the electrostatic analyser so that it falls on one or both of two electrodes. The current divides itself equally between the two if the energy of the beam is correct for the preset analyser voltage and magnetic field strength. However, if one or the other receives more current, a d.c. amplifier observes the error in the voltage of the machine by means of this current difference. If the energy of the machine is too high the beam is not deflected as much due to the greater velocity of the particles and the current increases on the upper electrode.

The difference in the current to the d. c. amplifier changes the bias on a pentode to control the corona current from the lower accelerating section of the Van de Graaff. The corona current is induced by a set of needles which are supported by the outer tank of the machine and point towards the large shell. This system can be seen in the upper center of Fig. 1. The overall control circuits are adjusted to reduce hunting and to achieve the closest adherance to the correct energy. The charging rate, i.e., belt current, is changed if the machine energy is consistantly being corrected in one direction.

The voltage of the machine is established by the operator in the following way. First, the electrostatic

analyser and magnetic analyser are adjusted to the proper electric and magnetic fields, respectively, and then the belt current is increased manually until the automatic control locks in. The voltage on the electrostacic analyser determines the energy at which the beam is to be held. To change the energy of the beam it is only necessary to change the analyser voltage. If this change is slow enough the machine energy automatically tracks. The magnetic analyser is adjusted at the same time to keep the beam into the electrostatic analyser.

The accuracy of the accelerating voltage of the Van de Graaff is directly related to the accuracy of the voltage on the electrostatic analyser. The analyser voltage is controlled by reference to a Rubicon potentiometer which is accurate to one part in ten-thousand. The overall control is expected to be within 0.1 per cent during proper operation.

4. Proton Beam and Rotating Target

A current of up to 5 microamperes of protons was obtained and controlled by adjusting the ion source. This beam is directed down a target tube which is horizontal and six feet above the floor. The target tube is terminated by a shutter and a rotating target.[1] The shutter is operated electrically from the control console by a switch which simultaneously starts and stops the scalars. The target tube is ten feet long and places

the source of neutrons about 15 feet from the massive end of the tank which forms the outside of the Van de Graaff. The scattering of neutrons from the floor is much greater than from the tank.

The rotating target is insulated from ground so the beam current that falls on the target may be measured by a current integrator. Since the current is a good measure of the actual number of neutrons being produced, the current integrator is a monitor for the data taken. An oven for evaporating lithium on to a tantalum target disc is contained within the rotating target. The target is rotated so the heat produced by stopping the beam may be dissipated over a large area. This prevents burning a hole in the tantalum disc and retards the oxidation of the lithium and the evaporating away of it.

The range of neutron energy[1] available to the neutrons produced by the known reactions is from 10 kev to 20 mev. This range is one of the most valuable properties of a Van de Graaff with an energy maximum of four to six mev.

I - b CONSTRUCTION OF NEUTRON COUNTER TUBES

1. Introduction

The initial step to start the measurements reported herein was to construct the neutron counter tubes suitable for the measurements planned. Initially, suitable neutron counter tubes were not available and the problem was to design and construct ones for these experiments. The counters were suitable for these measurements and for the other experiments anticipated for the machine. The result was two types of counters which are described below. Additional stand-by counters of the exact same design have been constructed because of the excellent performance of the initial counters.

2. Required Characteristics of Neutron Counters

The efficiency of a counter is an important factor in the measurements of the type in this thesis and, in general, for those with a Van de Graaff. The total number of counts for each measurement determines the statistical error in the data. The number of counts is usually made as large as possible to keep the errors small. A high efficiency counter enables the counting time to be reduced to a minimum. This is very important since the neutron flux is small[8] and in order to obtain high energy

resolution a small solid angle is subtended by the counter. Other factors, which are important, are freedom from counting gamma rays, microphonics and pick-up from the electrical system of the laboratory. The latter is determined by the electrical arrangement of the counting system including the scalars, amplifiers, power supplies, etc.

3. Mechanism in the Counting Tube

The design of the counters was based on achieving the best counting rates and avoiding the difficulties mentioned above. The nature of the counting arrangement, the background, the solid angle necessary for high energy resolution and the electronic requirements of the amplifiers and scalars determined the additional requirements on which the design was based.

Counters for measuring neutrons use the following nuclear reaction[9] in their operation.

$$B^{10} + n^{1} \longrightarrow B^{11*} \longrightarrow Li^{7} + He^{4} + Q$$

Since this is an exoergic reaction, i.e., Q is positive, the alpha particle and the lithium nucleus have kinetic energy which ionizes the gas filling of the tube. Thus this reaction can be used in counting thermal neutrons. The ionization causes a pulse to be registered by the tube if the current is sufficiently large. The process of gas amplification[10] is used to insure a pulse sufficiently large to be counted. In the case of very high

gas amplification the tube cascades into a discharge, as in a geiger tube, and the output pulse is independent of the energy which initiated the pulse.

The size of the pulse in case of moderate gas amplification is dependent on the energy of the neutron, because the energy given to the alpha particle and the lithium nucleus by the neutron increases the initial amount of ionization. To use the pulse size, the additional amplification is obtained in the electronic equipment attached to the counter. When a linear amplifier is used the size of the final pulse is a measure of the neutron energy. Such operation is in the proportional region of the tube and the counter is called a proportional counter. Another advantage of the proportional counter is its short dead time of about 10^{-6} seconds. It is several hundred times faster than a counter tube operated in the geiger region.

The boron counters[10] may be made in two ways. The counter walls may be covered with a boron compound, usually boron carbide, and the tube filled with an inert gas which will act as the ionizing medium. The other type of neutron counter is the BF_3, boron trifloride, counter which has as its gas the BF_3 and the nuclear reaction takes place within the gas itself. It was decided that this type would be better for the measurements planned. Since the

B^{10} is only 19 per cent abundant[11] as an isotope in natural boron, the efficiency of the counter is increased by the enrichment of the B^{10} isotope in the BF_3. The counters were filled with BF_3 enriched to over 90 per cent in B^{10}.

Another factor in the design of the counters is the voltage required for their operation. It is desirable that the voltage be reasonable, i.e., obtainable by conventional and available power supplies. The limitations placed on the voltage required by the counter tube is that it be less than 3000 volts, and preferably, considerably less, i.e., about 1000 volts.

4. Design Calculations

The choice of a gas amplification factor of 100 was based on previous practice at the laboratory and data available from the war time reports of several laboratories, particularly Los Alamos. The design calculations below are principally the conversion of data from other counters to the dimensions and characteristics of the ones under design and construction. This data has since been assembled by Rossi and Staub.[10]

The assumption, which is substantiated by experiment, is that the gas multiplication is a function of the form

$$M = M\left[\frac{V_o}{\ln(b/a)}, \quad pa\right] .$$

M is the gas multiplication, V_o is the voltage across the counter, a is the radius of the wire, b is the radius of the cathode, and p is the pressure of the gas. If the terms in the function are altered in such away that the overall value does not change the gas multiplication remains unchanged. Thus a and b may be multiplied by the same constant and provided the pressure, p, is divided by that constant, M is unchanged. This implies that the ratio between the mean-free path of the electrons in the gas and the electric field strength is unchanged. Using this and the data available it is possible to confirm the performance of the particular design in mind.

The following calculation is based on this procedure.

Dimensions chosen for counter:

Inside diameter - 1.00 inch

Wire diameter - 0.002 inch

Gas multiplication - 100 (Moderate value)

Data from curve on page 83 in Rossi and Staub[10]

Gas multiplication - 100

Inside diameter - 1.56 inch

Wire diameter -0.001 inch

Pressure -80.4 cm of Hg.

Counter voltage - 2650 volts

Consider the term :

$$\frac{V_0}{\ln(b/a)} = \frac{2650}{\ln(1.56/.001)} = \frac{V_o}{\ln(1.00/.002)}$$

$V_0 = 2240$ volts

also

$p\,a = 80.4 \times 0.001 = p\ 0.002$

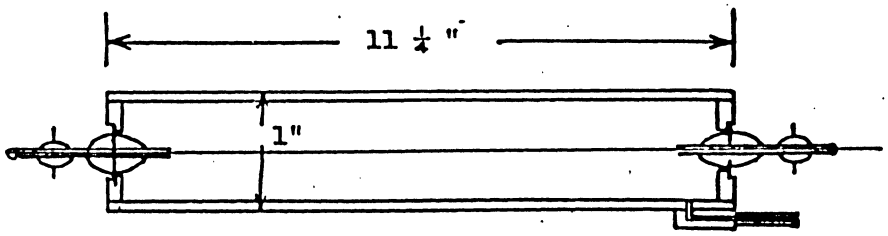
$p = 40.2$ cm of Hg.

Thus the voltage is within the limit set forth above, and the gas pressure in the counter being designed should be 40.0 cm of Hg.

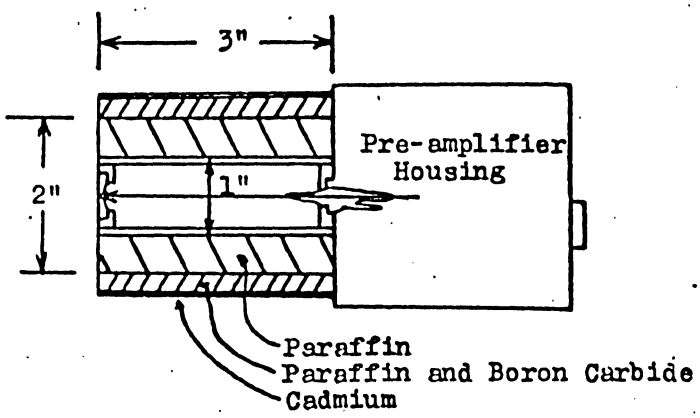
The diagrams, Fig. 4, show the general construction of the two types of counters. The differences are substantial in size and appearance but the calculations for gas multiplications are the same. The long counter was made and tested several months before the short counter was found to be required. The unsatisfactory nature of the long counter for the measurement of cross-section is discussed in the section on background measurements.

5. Counter Operating Characteristics

The curve showing the operating characteristics of the long counter is Fig. 5. The plateau that appears is not the same as the plateau in a geiger tube. It does not represent a constant counting rate with



Long BF_3 Counter



Short BF_3 Counter

Figure 4

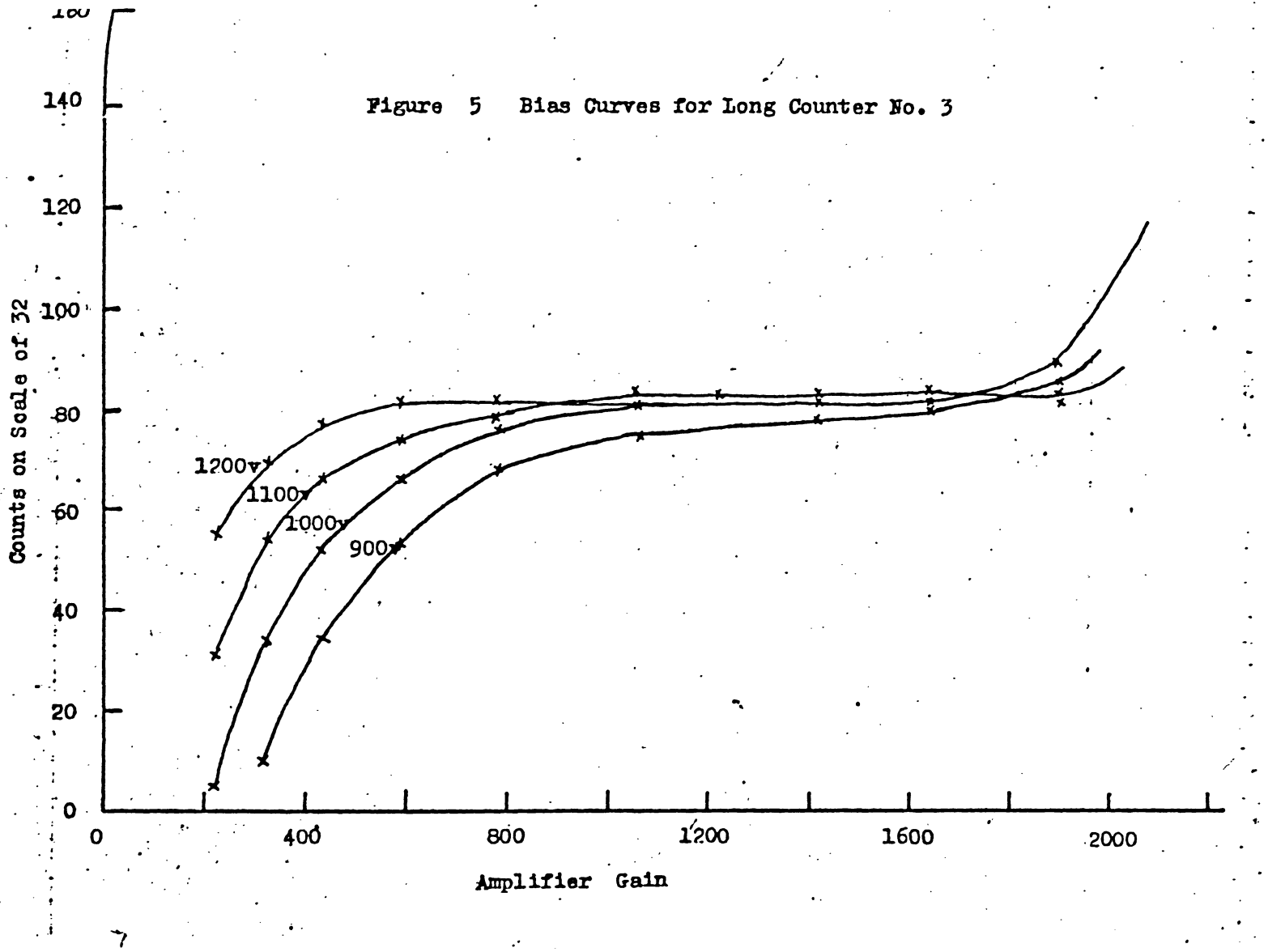


Figure 5 Bias Curves for Long Counter No. 3

voltage but a constant counting rate with the amplification of the linear amplifier[12]. The pulse size has an effective minimum within the counter tube, due to the exoergic reaction, and the gain in the plateau region is sufficient for virtually all the pulses to be counted. The output pulse of the linear amplifier is large enough to trigger the scalar for the smallest real pulse. The rise at the right end of the curve is not due to a continuous or spurious discharge in the counter. In this case, the amplification is so large that the noise of the counter and the preamplifier is being counted along with the true pulses from the neutron-boron reaction.

The operation at lower voltage than that calculated indicates the total gas amplification is not required with the amplifiers used. The increase in the width of the plateaus is due to the greater gas multiplication at higher voltages.

As a word of caution, these tubes can be damaged by spurious counts or discharges which are caused by too great a voltage. The counters have a definite life, as do geiger counters, but they are not refilled[13] because of the corrosion by the fluorine in the counters when they are opened.

6. Counter Assemblies

The long counter was placed in a cylinder of paraffin to increase the counting efficiency of the counter. Since the cross-section of boron[14] increases as the energy of the neutrons is reduced to thermal values, i.e., 1/40 ev, the moderation of the neutrons by the paraffin is an effective way of increasing the counting rate. The increased size of the counter assembly in the measurements of neutrons from a spot source, which are energy dependent on angle, makes the energy resolution poor.

The short counter is enclosed in a small amount of paraffin in order to increase the counting efficiency but limited to maintain energy resolution. This counter is patterned after one used by Seagondollar and Barshall[15]. The use of the spider support for the wire is a useful innovation and increased the effective length of the counter.

The circuits used with the counters are convential and thus will not be discussed. They may be seen in Elmore and Sands[16]. The preamplifier and the cables that ran to the linear amplifier were shielded to prevent pick-up of electrical noise resulting from the control circuits of the Van de Graaff. Voltage regulated a. c. power supplies were used to avoid changes in the amplifiers due to the variations in line voltage.

7. Resolution Time of the Counting System

The resolution time[10] of a counting system must be as low as possible so as to avoid coincidence loss in the counting of random events. In order to measure the resolution time, the complete equipment, i.e., short counter, preamplifier, linear amplifier, scalar, power supply and the mechanical register, were taken to the graphite reactor[17] (the original neutron chain reactor rebuilt at Site A of Argonne.) The counter tube was placed in one of the experimental holes and the control rods were withdrawn from the pile. The rise in neutron flux is exponential and the counting rate increased exponentially until the counter equipment could no longer count as rapidly as the flux rise indicated it should. The failure of the counter system to keep up is due to the dead time of the counting system. The departure from the exponential rise is noted and correction[10, 18] may be applied to account for the loss of counts. The counting system followed up to 10^6 counts per minute before an error of as much as 1 per cent. Since none of the data in this thesis ever reached, or even closely approached, this rate no correction was applied to the experimental data. The resolution time of the system was 12 microseconds. The mechanical register[19] was the initial limiting piece of equipment.

The data on the counters used are tabulated below.

	Long Counter	Short Counter
Length	$11\frac{1}{4}$	3 inches
Inside Diameter	15/16"	15/16 inches
Wire Diameter	.002	.002 inches
Filling	BF_3, enriched	BF_3, enriched
Pressure	40.0	40.0 cm of Hg.
Outside Diameter	1.00	1.00 inches
Resolution time		< 12 microseconds

I - c · Calibration of Counters

1. Introduction

The calibration of the counters was started upon their return from the group[20] that filled them with the BF_3 to the pressure specified. The proper performance of the counters is essential for successful experiments and must be obtained before the construction of the counters could be abandoned and the other phases of the measurements started.

A Ra-Be[21] source of neutrons was used initially in the calibration. There were two sources actually used in the calibration, one which weighed 1 gram and the other which weighed 500 milligrams. The neutron flux from such a source is of the order of 10^6 neutrons per second over the entire solid angle. This insures a high counting rate for a counter placed near the source and the rate was further increased by surrounding the counter by paraffin to thermalize the neutrons.

2. Electrical Arrangement

First the counter was tested to insure that it would withstand the voltage across it with out breakdown and that the resistance from the wire to the tube was very large. This indicated no shorting within

the counter tube due to soldering, corrosion, or contamination of the insulators.

The operation is in the proportional region where the pulse size is proportional to the neutron energy and other factors. The amplifier used with the counter consists of two parts. One is the preamplifier[16] attached to the counter and its power for filaments is supplied by the power circuits of the linear amplifier, the second part. The high voltage is supplied by the separate high voltage regulated power supply. The output of the preamplifier and the power for it are fed through cables to the input of the linear amplifier. Since cables are quite susceptable to picking up external signals, it was necessary to put a metal sheath around the cables and ground the entire system. This removed any counting from external noise not in the building power lines as electrical noise. Additional precautions were necessary to remove this wire conducted noise. The a c voltage regulators were helpful and the filter circuits in the power supplies of the amplifiers and scalars removed it from being effective in causing counts. A c line filters were also used.

3. Extraneous Counts

The method of testing for extraneous counts was to adjust the counters to the proper voltage and

amplification for normal counting and remove the source of neutrons to a large distance and observe the background. Under these conditions the background is small and of the known value for that location. Furthermore, the counts from noise is different in nature from the legitimate counts. The noise counts come in bursts and the scalars quickly accumulate many more counts. The counting appears as an avalanch and the noise can be plainly seen on an oscilloscope and distinguished easily from other signals. Through all the experiments the counters were checked for any extraneous counts by observing the background and the nature of the counting.

4. Linear Amplifier

The pulses were amplified by the linear amplifier[12] and were attenuated prior to being fed to the output circuit of the linear amplifier. The output circuit selected pulses of sufficient size, and for each acceptable one, triggered a univibrator which gave a uniform pulse, several volts high, to the input of the scalar. This made the counting rate independent of the particular scalar used since the pulse was always large enough to insure a count being registered on any of the scalars available. This eliminated one variable

and improved the counting arrangement.

The output of the linear amplifier prior to the univibrator could be fed directly to a discriminator to distinguish between the different size pulses as a measure of neutron energy. Another use of the latter output was for observing the nature of the pulses and background noise in an oscilloscope.

5. Gamma-ray Sensitivity

The gamma ray sensitivity of the counters was checked using an intense gamma ray source, a radium sample, placed along side the counter during the background checks. The failure to count the gamma rays was ovserved and desired. It is important not to count this type of radiation because of the high energy X-rays given off by the Van de Graaff. During these measurements the maximum energy of the accelerator is 3 mev and the X-rays have up to this energy. There is an additional possibility that the reactions caused by the protons or, more importantly, by the neutrons in the materials near the counter during the measurements may involve a gamma radiation. This would increase the background, if counted.

6. Periodic Check of Counting Sensitivity

Periodic checks of the entire counting system, including all the electronic components, were made using a small Ra-Be source, about 10 milligrams. The small source was placed adjacent to the counter in a reproducable position and the counting rate was measured over many minutes while the machine was not running. The counting rate should not be different from day to day if the characteristics of the counting system remain unchanged because the half life[11] of the Ra-Be source is so large. This check is useful for learning of deterioration of the counting system but does not reveal any difficulties during the experimental measurements since then the counting rate is so high that the presence of the cascading counts is not observable. Also any saturation or hystersis effects are not observable in this way. These effects were not considered to be important because of the performance of the system during the measurements of the resolution time.

I - d Lithium (p, n) Berylium Reaction [8]

1. Introduction

The precise energy control of the Van de Graaff is only one factor in the control of the energy of the neutrons produced by it. The second factor, of the same magnitude as the uncertainity in the energy of the accelerator, is the spread in the energy of the neutrons from the reaction in the target. Firstly, this is due to the creation of neutrons at any place in the target from the side toward the proton source to the layer farthest away from it. Secondly, it is due to the variation of neutron energy as a function of angle.

Since the protons are charged particles they lose energy in going from the first side to the latter in the lithium film. The amount of energy which is used in this process is the energy thickness of the target. Neutrons are not effected by this phenomena and thus the energy variation is dependent directly upon the position in the target at which the reaction takes place. The maximum variation, due to this cause, is the energy thickness of the target.

The target thickness may be determined by the experimenter and usually is from 1 kev to 100 kev depending on the type of measurements that are planned. For high resolution work the target is made quite thin,

while for measurements that are intended to show the mean or average cross-section the targets are purposely made thick in order to accomplish this averaging.

The yield of the target is proportional to the amount of material present in a target. For this reason a compromise of target thickness with energy resolution is made. An increase in target thickness results in a more efficient use of the counting time. In most cases the statistical accuracy, which depends on large numbers of counts, is of equal importance to the energy resolution and there is a limited time in which to do the work since the use of the accelerator is expensive in manpower and cost. The determination of the target thickness is based upon the actual measurement being attempted. There are no limitations in the accuracy except the time and cost.

2. Li(p,n)Be Reaction

The neutrons used in these measurements of total neutron cross-section were obtained from the Li(p,n)Be reaction. The reaction is as follows.

$$Li^7 + H^1 \rightarrow Be^7 + n^1 + Q$$

This reaction is endoergic, thus Q is negative.

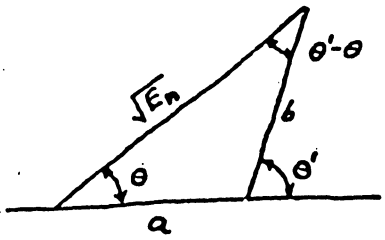
From the observed threshold in the laboratory system of 1.882 mev,[7] the Q of the reaction is - 1.65 mev.

The high threshold causes the velocity of the center of mass, as seen in the laboratory system, to be considerable. This results in the neutrons at energies just above threshold being concentrated in the forward direction even though the reaction is isotropic in the center of mass system. For this reason there are two energy groups of neutrons in the forward direction until the proton energy is well above threshold. The lower energy group, as measured in the laboratory system, becomes directed to 180 degrees in the laboratory system when the neutron energy of the forward group is equal to or greater than 130 kev. The measurements in the forward direction, i.e., at zero degrees, are taken only above 130 kev.

For measurements with neutrons of less than 130 kev, monoenergetic neutrons obtained at angles greater than 90 degrees are used. These measurements are referred to as back angle work. In these measurements the back angle of 120 degrees in the laboratory system was used.

The velocity diagram of the reaction is given below.

Velocity diagram.



where E_n is the neutron energy

θ is the angle in the laboratory system

θ' is the angle in the center of mass system

a is proportional to the velocity of the center of mass

b is proportional to the velocity of the neutron in the c of mass system.

The solution of the diagram gives the following relations.

$$E_n = a^2 + b^2 + 2ab \cos \theta'$$

$$= a^2 \cos 2\theta + b^2 + 2a \cos \theta \sqrt{b^2 - a^2 \sin^2 \theta}$$

$$b^2 = 0.762 \left(E_p - E_{th} \right)$$

$$a^2 = E_p / 63.35$$

$$\theta' = \theta + \sin^{-1}\left(\sin \theta / (b/a) \right)$$

For this reaction with the threshold of 1.882 mev and the angles chosen and for typical values of proton energy these reduce to the following.

Forward Direction	Backangle at 120°
E_p = 2500 kev.	E_p = 2500 kev.
a = 6.29	a = 6.29
b = 21.75	b = 21.75
E_n = 784 kev.	E_n = 175 kev.

The backangle of 120 degrees was chosen for several reasons. Firstly, this angle, which is measured in the laboratory system, is convenient as a position for the counter. At any greater angle the target tube prevents the equipment from being moved into proper position. Secondly, the proton energy required for the low energy neutrons at this angle is obtained at moderate machine voltages. Thirdly, it is free from double energy neutron fluxes.

3. Measurement of Target Thickness

The measurement of the target thickness is made by observing the increase of the neutrons flux immediately above the threshold. The machine is operated at a few kilovolts below threshold and the energy is gradually increased in small increments to about 20 kev above threshold. The rise in the neutron flux is plotted as in Fig. 6 and the following calculation is made.

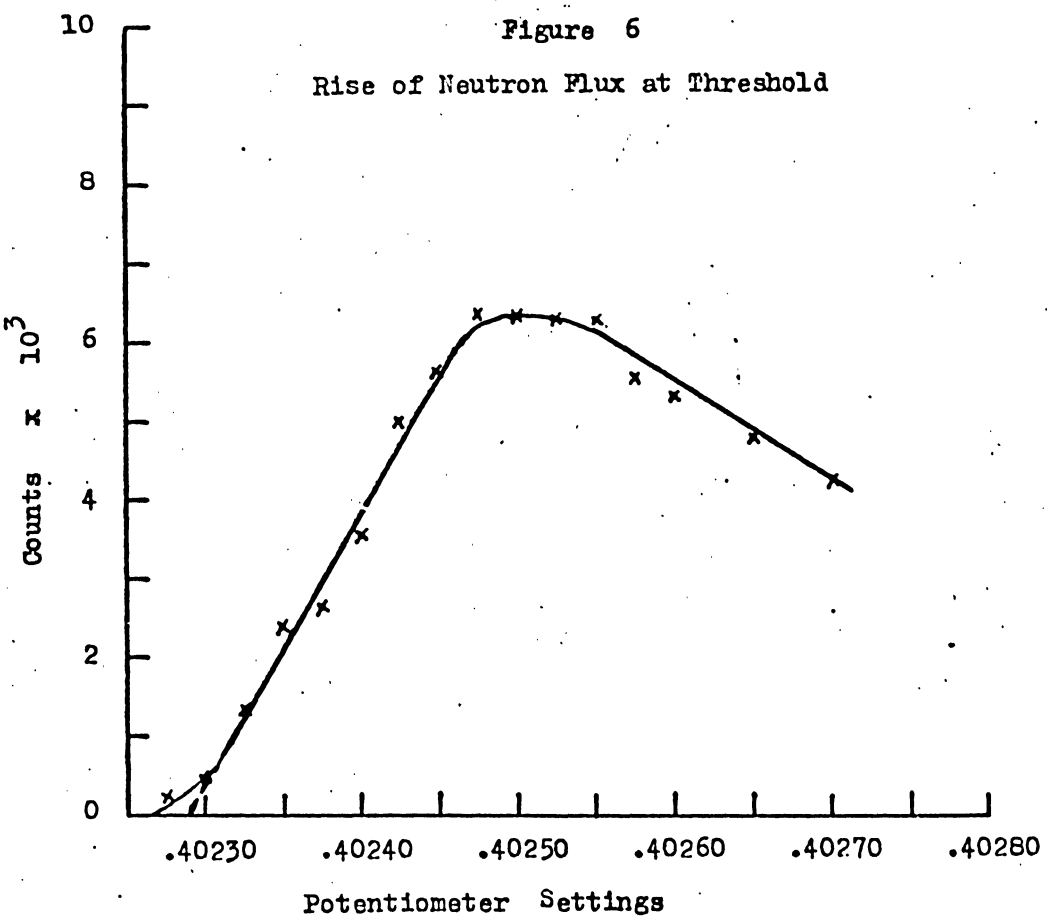
$$\text{Target Thickness} = 1.882 \times \frac{\text{Pot. setting at end of rise} - \text{Pot. setting at threshold}}{\text{Potentiometer setting at threshold}}$$

$$= 1.882 \times \frac{4050 - 4036}{4036}$$

$$= 6.0 \text{ kev}$$

Figure 6

Rise of Neutron Flux at Threshold



Target Thickness $\frac{.00225}{.40240} \times 1882$

10.5 kev

This process is repeated during the experimental measurements in order to check upon the condition of the target. The target may change in two ways during its use. If the temperature gets too high the lithium may be evaporated away. This seldom happens, but the heat may accelerate the oxidation of the target. As the lithium is oxidized it becomes thicker due to the additional material present. This thickness is an increase in the energy thickness of the target, just as the depositing of more lithium would be, but the yield does not increase. The growth of the target is proportional to the age of the target if the vacuum is good and maintained constantly.

When the target thickness has reached a value that is excessive a new target is placed on the disc. The vacuum system is arranged so that the target tube may be cut off from the rest of the system and let 'down' to air. The old target is removed by washing the target disc with distilled water.

The new target is replaced by evaporating the lithium on to the tantalum disc while the disc is in place on the machine and the target tube is at a good vacuum. The machine is operated at an energy well above threshold and the thickness of the target is monitored as it is being deposited. At this energy of the machine,

the counting rate for the desired target thickness is calculated prior to the start of evaporation of the lithium. The counting rate is also dependent on the position and efficiency of the neutron counter used as a monitor. Once an initial target has been placed on the machine and its thickness measured there is enough data to calculate the conditions for any subsequently desired target thickness. The position and counting efficiency is carefully reestablished in order to use the initial data accurately.

When this counting rate is achieved, the evaporator is quickly pulled away from the target face and the electrical heater is turned off. The machine is then adjusted to operate at the threshold energy and the new target's thickness is measured. If it is satisfactory the machine may be used for the experiment in mind, otherwise the new target is removed and replaced in the same fashion.

Since an increase in the energy thickness of the target is anticipated with use, a slightly thin target may be placed on the machine. This is not necessarily expedient since the increase in the counting time due to the decrease in yield may be greater than the time required to replace the target more

frequently. The data from each target is usually indicated by a different symbol.

4. Monitoring the Neutrons

The neutron flux may be monitored by two methods, one a counter, called the monitor, and the other, a current integrator. In the measurements described below the monitoring was accomplished in two ways and the most independent way was use to normalize the data. However, the alternate way was a useful check on the other and continually used for this purpose.

A current integrator is used in this work to monitor the proton beam current. The neutrons yield is dependent on the proton beam current and equal intervals in beam current is more indicative of the unit of neutron flux than an interval of time. This is true of all measurements of the type taken with a Van de Graaff. The neutron yield is normalized by a fixed number of current units. The unit of current is not important, as long as it is the same for all the data, i.e., the initial target thickness data upon which the calculations are based and the data for the new target. During the measurements it is necessary that it not be changed over any set of data. The proton current is a better neutron

monitor than time, since if the machine sparks or the beam current changes the neutron flux is not a known function of time.

A better and more accurate way of monitoring the neutron flux is by the use of an independent neutron counter. The difficulty of its use arises from the changes in the neutron flux to it, due to changes during the experiment. The addition of the scattering sample into the neutron flux may scatter additional neutrons into the monitor counter.

5. 10 per cent Yield of Neutrons[22]

During the time of cross-section measurements there was found that the Li(p,n)Be reaction had another yield of neutrons which appear when the energy of the known neutrons is above 640 kev. The yield of this second reaction is believed to be about 10 per cent of the yield of the first reaction.

The energy of these neutrons is much less than those from the initial yield. The efficiency of the counters is higher for the low energy neutrons, thus their presence in the neutron flux for the measurement of cross-section above 640 kev neutrons might modify the data in that region. It is expected that the low energy data will be superimposed

on the higher energy data. It is possible that the low energy structure might be recognizable in this region if the high energy cross-section is rather smooth. The effect would be at least as great as the percentage of the yield.

The neutron cross-section data was examined for this effect which was not found, or at least the nature of the effect could not be determined. Therefore, no correction was made to the data for this effect. The information available on the 10 per cent yield is not complete enough to warrent any arbitrary correction to the data.

PART II MEASUREMENT OF THE TOTAL NEUTRON CROSS-SECTION OF COBALT AND MANGANESE AND OTHERS

II - a Introduction to the Measurements

1. Reasons for the Measurements

The measurements of the total neutron cross-sections for cobalt and manganese and the preliminary cross-section measurements of other elements were made for several reasons. The primary reasons are the following:

a. The neutron cross-sections of these elements were not available and were needed for calculations in the design of nuclear reactors and for other purposes.

b. The elements were related to each other in a unique and interesting way.

c. Measurements of this type were suitable for the initial use of a Van de Graaff. Earlier data from other machines were used as a check on the performance of the new machine by repeating selected measurements.

d. The equipment constructed and assembled is comparatively simple and useful for many purposes,

e. The measurements could be made in a limited time.

f. Work of this type is unclassified and publishable.

2. Transmission Measurements

The measurement of total neutron cross-section is a transmission type measurement. It is assumed that the neutron is scattered only once or enters only one reaction in passing through the sample. The thickness of the sample must be made to conform with this latter assumption, i.e., be not more than one mean-free path thick. The cross-section is calculated by the following formula:

$$I = I_o \exp(-n\sigma x)$$

thus

$$\sigma = \frac{\ln(I/I_o)}{-nx}$$

where: I_o is the intensity of the neutron beam with no sample in the beam,

I is the intensity of the neutron beam with the sample in the beam,

n is the number of atoms per cubic centimeter in the sample,

x is the thickness of the sample in centimeters,

σ is the total neutron cross-section in barns, i.e., 10^{-24} square centimeters.

nx is the number of atoms per square centimeter of the surface of the sample. The sample must have parallel faces and uniform density.

nx is calculated by the following formula:

$$nx = \frac{\text{(Avogradro's Number)} \quad \text{(Weight of Sample)}}{\text{(Atomic Weight)} \quad \text{(Area of Sample)}}$$

The reactions that take place as the neutron passes through the sample are:

a. Capture- The neutron may be captured by the nucleus and it is transformed by the addition of one neutron. The nucleus may then remain in this state, if it is a stable state, or more likely, the nucleus may be transformed to another state or nucleus by radioactive decay. Such decay is known as artificial radioactivity and follows a radioactive decay process in accord with the natural laws governing those processes.

b. Elastic Scattering- The neutron may be elastically scattered and removed from the direct beam. If the sample subtends more than the same solid angle as the detector from the source of neutrons, some of the neutrons which would not have been counted by the detector are scattered into the detector and are counted. Such scattering is called scattering-in

and introduces an error in the data. The correction of the data to account for this is discussed later.

c. Inelastic Scattering- The neutron may be scattered inelastically and removed from the beam. The inelastic scattering reduces the energy of the neutrons. The inelastically scattered neutrons may also contribute to the scattering-in error. In this case, the counter is more sensitive to these neutrons because of their lower energy.

There are other nuclear processes possible but are not considered to make any contribution to the measurements at the energies of these measurements.

The total neutron cross-section is the sum of the individual reaction cross-section.

$$\sigma_t = \sigma_c + \sigma_i + \sigma_e$$

where σ_t is the total neutron cross-section

σ_c is the capture cross-section

σ_e is the elastic scattering cross-section

σ_i is the inelastic scattering cross-section.

The unit of cross-section is a barn which is 10^{-24} square centimeters.

3. Compilation of Neutron Cross-sections

In preparation for this work a search for the neutron

cross-sections of all elements was made. A compilation of unpublished cross-section measurements was made in the form of a laboratory report[23] and distributed to interested groups. Between the time of these measurements and the present, a compilation of neutron cross-sections has been made by Adair[14]. The cross-sections of cobalt and manganese discussed below appeared in Adair's compilation. All the measurements have appeared in the progress reports of the Argonne National Laboratory[24].

II - b Initial Group of Elements

1. Choice of the Elements

The elements chosen for the initial measurements were scandium (A= 45, Z= 21), vanadium (A=51, Z=23), manganese (A=55, Z=25), and cobalt (A=59, Z=27). Later as the measurements were being started, columbium (also calledniobium, A=93, Z=41) and cerium (A=140-142, Z=58) were made available to the Van de Graaff group with a request to include them in our measurements.

The first four were chosen on the basis of the relation their nuclei have to one another. They have similar nuclei and vanadium, manganese and cobalt each differs from the previous by the successive addition of a helium nucleus, i.e., two protons and two neutrons.

The unique relation between the nuclei,plus the fact that none of these had been measured at neutron energies above several kilovolts made them of great interest. Another factor is the isotopic abundance. All four are single isotopes,[11] i.e., 100 per cent abundant, so that the structure of their neutron cross-sections might be resolved. In elements of many isotopes the neutron resonances are different for each isotope and the combination masks the nature of each. For these,

if the structure is to be resolved the isotopes must be separated and examined individually.

The resolution of the structure of the neutron cross-section is of great value in confirming the theoretical predictions. These elements were expected to have similar cross-sections because of the similarity of their nuclei. The resolution of structure depends upon the energy precision of the machine and the thickness of the lithium target. The selection of a thin target was in the effort to resolve the structure.

2. Exclusion of Scandium

Scandium is a rare element and the amount available in a purified form is quite small. It is only available as scandium oxide and not in the quantity required for the measurement technique used at this time. The measurements of scandium was thus abandoned.

3. Physical Characteristics of the Samples

The samples of cobalt, manganese, and vanadium were obtained from the special materials group of the laboratory. The samples were known to be of high purity and had been obtained for experimental purposes by the laboratory. Since they were special it was decided not

to alter their form for these measurements, although their sizes were not the desired sizes. The thicknesses of the samples were satisfactory for the initial assumption of a single neutron process occuring, since the thicknesses were less than a mean-free path. The diameter of the vanadium was satisfactory but the diameters of the cobalt and manganese samples were too large. This caused a sizeable scattering-in error.

A spectro-chemical analysis of the purity of the manganese sample, made by the Chemistry Division of the Argonne National Laboratory, showed the total impurities were less than 1 per cent. No single element was present as an impurity of more than 0.1 per cent.

The columbium and cerium samples were in powder form and packed tightly in aluminum cans which were sealed with zapon lacquer. Similar empty cans were provided to be used as duplicates for measuring the direct beam. These cans were spun out of thin aluminum and were alike as far as examination, measurement and weighing could determine.

The columbium and cerium were measured because of the interest in them by the reactor development people at Argonne. Only preliminary measurements were made on these two. These measurements were useful since the magnitude of the cross-sections were desired rather than the details of resonance structure.

The values of the important characteristics of he samples are as follows:

	Vanadium	Manganese	Cobalt	Columbium	Cerium
Mass Number	51	55	59	93	140 142
Atomic Number	23	25	27	41	58
Atomic Weight	50.95	54.93	58. 94	92.91	140.13
Isotopic Abundance	100%	100%	100%	100%	88.43% 11.07%
Thickness in Cm.	2.54	1.596	1.174	2.54	2.54
Diameter in Cm.	4.40	7.62	7.62	4.40	4.40
Weight in grams	238.5	530.15	470.17	147.15	231.46
Atoms per sq. cm.	0.1815×10^{24}	0.1275×10^{24}	0.1053×10^{24}	0.0675×10^{24}	
Atoms sq. cm.					0.0690×10^{24}--Cerium

II - c Arrangement of the Target, Sample and Detector

1. Experimental Requirements

The arrangement of the target, sample, and detector was made on the basis of the following experimental requirements:

a. The counting rate required for economical use of the time.

b. The energy spread in the neutrons which is a function of the angle subtended by the scatterer and the detector.

c. The physical limitations in placing the scatterer and detector.

The detector was placed 12 inches in front of the target in line with the target tube for the 0 degree measurements. The scatterer was placed midway between the spot source of neutrons on the target disc and the detector. The scatterer was supported in a reproducable manner by a triangle of steel piano wire. The wire support added very little material to the scattering system and was in position at all times. It made the same contribution to the direct beam measurements and background measurements as to the measurements with the scatterer in place. Its effect on the cross-section is believed to be insignificant.

The diagram of the support is given in Fig. 7, while the arrangement of the elements is shown in Fig. 8.

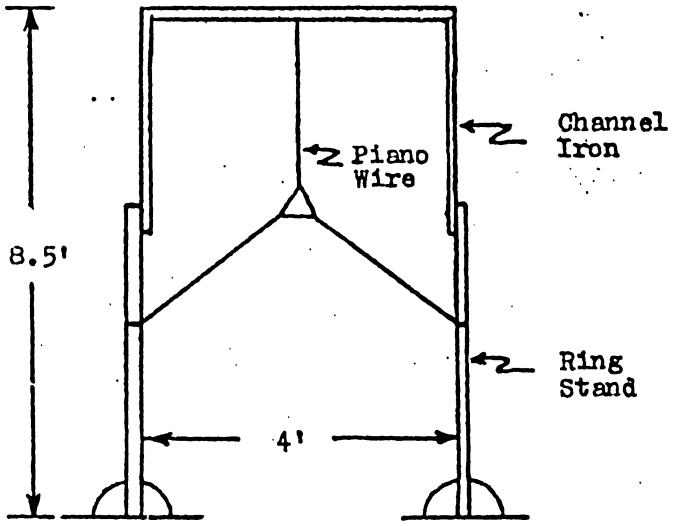


Figure 7 Sample Support

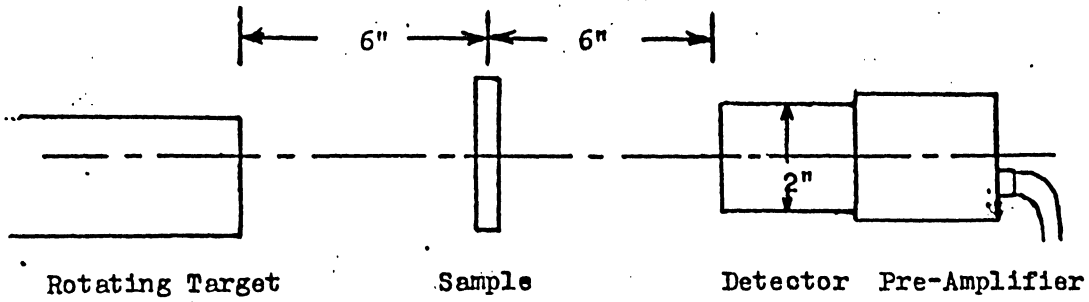


Figure 8 Arrangement for Counting at 0^{o}

Fig. 9 shows the arrangement for the backangle work.

The actual position of the neutron source, i.e., the spot where the proton beam strikes the rotating tantalum disc, was found by holding a piece of temp-stik against the tantalum disc when it was not rotating and observing the position and size of the spot at which it melted. Frequent checks of the position of the spot were made since it may shift due to the adjustments on the Van de Graaff. Such adjustments as the focusing voltage and the ion source or on the structural members of the machine. This method showed the spot source of neutrons to be about 3/8 inch in diameter.

The detector was attached to the preamplifier in the manner shown in Fig. 8. Note that it is included within the shadow of the counter and the back-scattering from it should be very little, if any. This arrangement was planned to avoid back-scattering. The supporting arm which held the detector was made as light as possible to avoid significant scattering by it. In any event, the scattering due to these components was unchanged through out the entire experimental period by not altering their positions during this time.

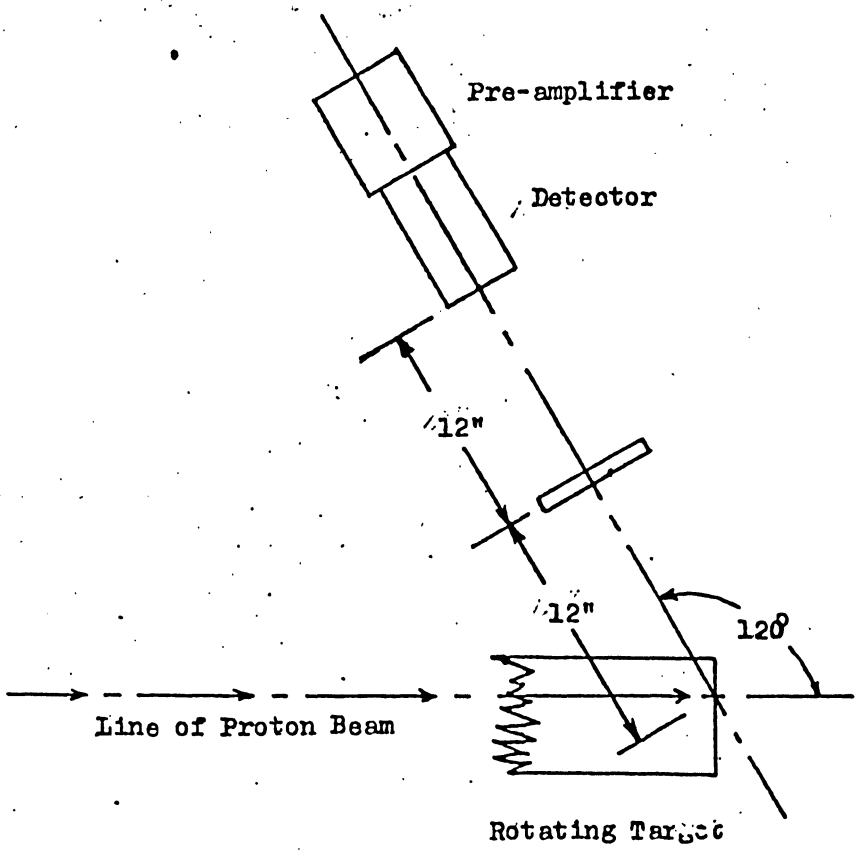


Figure 9 Arrangement for Counting at 120°

II - d Precision of the Measurements

1. Variations in Energy

The energy stability of the Van de Graaff was determined by the variations of the points from the mean curve of the rise of neutron flux at threshold. These measurements reveal the energy stability of the machine to be 4 kev. This uncertainity holds through out the data. The defining slits in the target tube prevent protons of a large energy difference from that expected from falling on the lithium target. The result of large proton energy differences, due to sparking or other faults with the machine, is to reduce the neutron flux to zero and increase the time required to obtain a predetermined number of counts.

The energy variations due to the thickness of the lithium may be calculated on the basis that the total difference in the neutron energy is due to the thickness of the target as measured in kev. In the forward direction this variation is 6 kev and the same in the back angle work.

The third uncertainity in energy of the neutrons is due to the variation of neutron energy as a function of angle. The angle subtended by the sample determines the range of the variation of the neutron energy, which is small for a small solid angle. Actually the plane angle is a good measure of this since the neutron

distribution is symmetrical about the line extended along the direction of the proton beam as it falls on the lithium target.

The use of a McKibben chart[1] shows this error to be as tabulated below for the different samples in their two positions.

Zero degree position.

	Diameter	Solid Angle	Plane Angle
Vanadium	1.75"	.0613	16°38'
Manganese	3.00"	.181	29°
Cobalt	3.00"	.181	29°
Columbium	1.75"	.0613	16°38'
Cerium	1.75"	.0613	16°38'

120 degree position

Vanadium	Not measured in the Backangle		
Manganese	3.00"	.0348	14°16'
Cobalt	3.00"	.0348	14°16'
Columbium	Not measured in the Backangle		
Cerium	Not measured in the Backangle		

The maxiumum and minimum variations in the neutron energy from all these sources are tabulated below.

	Maximum Energy Variation-Neutron Energy	
Zero degree position		
Vanadium	6 kev	500 kev
Manganese	10 kev	500 kev

Cobalt	10 kev	500 kev
Columbium	6 kev	500 kev
Cerium	6 kev	500 kev
120 degree position		
Cobalt	4 kev	100 kev
Manganese	4 kev	100 kev

2. Statistical Errors

Another source of error in the data, but not in neutron energy, is the statistical errors which arise due to the independent neutron processes in the target, in the scatterer, and in the detector. These errors are considered on the basis of the following assumptions:

a. The reaction of a proton which forms a neutron is independent of the formation of any other neutron.

b. The scattering or other process which takes place in the sample is independent of all other processes in the sample.

c. The number of neutrons actually counted is a samll fraction of the total neutrons involved in the experiment, i.e., the neutrons which go through the solid angle subtended by the detector from the spot source of neutrons.

d. During any counting interval or taking data, which are compared, added, subtracted, divided or referred

to one another in any way, there are no changes in the system excepting the presence of the scatterer or the background cone, and the counting efficiency of the system is not changed. The counting interval includes all the counts made at one time at one single energy setting of the Van de Graaff, specifically, the counting of the direct beam, the beam with the scatterer, and the background measurement.

e. The normal distribution of repeated measurements will be a Poisson distribution.

The statistical distribution is then calculated using the following formulae[18]. The standard deviation is defined, on the basis of our assumptions, as

$$\sigma = (n)^{\frac{1}{2}}$$

where σ is the standard deviation and n is the number of neutrons counted in the particular measurement. For the addition of data the standard deviation for the sum is given by

$$\sigma_s = \sqrt{\sigma_1^2 + \sigma_2^2 + \cdots}$$

where σ_1, σ_2, etc. is the standard deviation of each individual measurement.

For the subtraction of data the standard deviation of the difference is given by

$$\sigma_d = \sqrt{\sigma_1^2 + \sigma_2^2}$$

where σ_1 is the standard deviation of the minuend and σ_2 is the standard deviation of the subtrahend.

If the quotient of two data is $Q = R_1 / R_2$, the calculation of the standard deviation of the quotient is

$$\frac{\sigma_Q}{Q} = \sqrt{\left(\frac{\sigma_1}{R_1}\right)^2 + \left(\frac{\sigma_2}{R_2}\right)^2}$$

where σ_Q is the standard deviation in the quotient, and σ_1 is the standard deviation in R_1, etc.
If the product of two data is $P = R_1 R_2 \cdot \cdot \cdot$, the standard deviation of the product is

$$\frac{\sigma_p}{P} = \sqrt{\left(\frac{\sigma_1}{R_1}\right)^2 + \left(\frac{\sigma_2}{R_2}\right)^2}$$

where σ_p is the standard deviation of the product and the other terms are as above.

Note the probable error which is usually used in reporting data is related to the standard deviation by the following:

$$P = 0.674\,\sigma$$

where P is the probable error and σ is the standard deviation. The probable error is the value by which one half of the measurements will exceed or fall short of the mean or average of all the measurements. The probable error is often indicated by the size of the symbol indicating the point of data.

The following table indicates the dependence of the standard deviation in the cross-section as a function of the standard deviation in the transmission data. As seen on page 35, the cross-section is a constant

times the natural logarithm of the ratio of the transmitted beam to the direct beam. This ratio is called the per cent transmission, or simply, the transmission. Thus, the statistical error in the transmission is related to the statistical error in the cross-section by the logarithm. The following table of transmissions and cross-section errors indicate the relative size. The probable error is about two thirds of these values.

	Transmission Values				
	0.40	0.50	0.60	0.70	0.80
Error in T	1%	1%	1%	1%	1%
Error in σ_t	1.2%	1.6%	1.9%	2.5%	4.5%
Error in T	3%	3%	3%	3%	3%
Error in σ_t	3.3%	4.5%	5.9%	8.4%	13.0%

Note that in this table the symbol σ_t stands for the total neutron cross-section and the values given are the standard deviations in transmission and cross-section.

3. Errors in the Monitor

Another source of errors was the process of monitoring the neutron flux. Two monitoring methods are available to the experimenter. The first method is the use of a monitor counter placed at a fixed position and used to observe the neutron flux. Equal intervals in counting the direct beam and the transmitted beam is initiated by equal counts by the monitor. The monitor counts for any interval are used to normalize the data obtained. The second method is the use of a current integrator which accurately measures the proton current which falls on the lithium target. It is assumed, that since all the data is taken well above the threshold, the total neutron flux is proportional to the proton current.

In the use of a monitor, the statistical errors of the monitor enter the data. These can be reduced by using a very efficient counter for the monitor, and obtaining a large number of counts per interval. This implies a counter surrounded with a lot of paraffin and placed close to the source of neutrons.

The use of a current integrator is handicapped by the limited number of current intervals which can be measured by the recording unit on the integrator. The error in stopping the beam just after or just

before another click of the integrator may be as large as one full current interval. If the number of clicks is not large this error may be several percent. For this reason, the cut-off circuit was arranged to wait for the click on the integrator following the action of the experimenter and be activated by it. This removed uncertainity in the monitoring of the data and improved the accuracy of the data.

The system was arranged so that a single switch operates all of the scalars and the shutter. The operation of the shutter was slower than the electrical relays on the scalars. This allowed a unique check for spurious counts since it was possible to observe the interpolation lights on the scalars during the short interval after the scalars would record counts and the time the shutter had fallen out of the proton beam path initiating the counting due to the neutron flux.

This interval was sufficient to allow positive observation of spurious counts. Some times the interval was longer than desired, even for this purpose, because the intense heat on the quartz shutter made it stick in its guide. Since there were never any counts registered during this interval, its length made no error in the data. Similarily, the current integrator received no current during this interval.

The use of a neutron counter as the primary monitor was not advisable in these measurements, since the placement of the scattering sample in the neutron beam increased the neutron flux in the region of the monitor by scattering the neutrons out of the direct beam. Thus, in the direct beam measurements, the unit of monitored neutrons constitutes a larger total flux than in the measurements with the scatterer. This is due to the longer time required in accumulating the same number of counts in the monitor without the help of the additional neutron scattering due to the scatterer.

These measurements were normalized by reference to the current integrator. The monitor was used as a secondary reference. It brought to light any errors in the data because it was one of three independent measurements. The total counts on the monitor did not vary by large values due to the presence or absence of the scatterer.

4. Errors in Cross-section

The accumulation of errors from the above sources and the computation involving taking the logarithm result in a net error in cross-section. The net error in cross-section is a fundamental consideration in the presentation and interpretation of the data.

A study of these errors and their relative magnitudes indicate the precautions which are to be taken in experimental work and the relative importance of each precaution. Unnecessary accuracy in some measurements may be time consuming and not yield a corresponding improvement in the data.

Such is the case with background measurements when the background is a small fraction of the direct beam. In these measurements the background is a small fraction of the other two counts thus the standard deviation in it is a small fraction of the standard deviations of the other two counts. The length of counting to obtain the same accuracy, i.e., one per cent, in background counts is very large. It is expedient to use the background counts obtained in the same monitoring interval as used for the other counting, rather than counting background many times longer than the other counts.

A study of the best counting procedure for the measurements was made to determine the experimental arrangement best for the measurements and the best division of the counting time. An analysis by Rose and Shapiro[25] was most useful and suggests that for the transmissions used the optimum division of counting with the background shown is as in the following table.

Optimum Division of Counting Time

	Transmission		
	0.50@ m=1.0	0.60@ m=1.0	0.80@ 1.3
Direct Beam	23%	26%	30%
Transmitted Beam	40%	38%	36%
Background	37%	36%	34%

Where m is given by

$$M = \frac{V_2}{V_o - V_2}$$ where V_o is the direct beam counting rate
V_2 is the background counting rate

These divisions are not very critical with m.

This division was not rigorously followed but observed to some extent. Note, however, the use of equal counting intervals for all counts is a rather satisfactory division of the counting time. Actually the time lost in observing a detailed counting schedule destroys the advantage of doing so. As an example, the best use of counting time is important when the time available is very limited due to radioactive decay of short half life.

Since several of the samples could not be altered and since their cross-sections were not known prior to the measuremonts the analysis was not completely applicable.

Another effect of the sample thickness, or its transmission, is to slightly shift the cross-section because of the self-protection effect observed in neutron

absorption or transmission measurements. The self-protection comes from the selective use of neutrons of a specific energy by the sample which then removes them from the system. For example, assuming a capture process which is highly selective to energy, it will be seen that the neutrons of this energy will quickly be removed and the transmission will be small. The presence of additional material, i.e., a thicker sample, will not add equally to the subtraction of the neutrons. Since the calculation is based on the assumption that each atom per square centimeter contributes equally to the process an error is introduced. Thus for thick samples the cross-section is less than for thin samples in which each atom contributes to the removal of the neutrons.

For low cross-sections this process is useful in determining the depth of the hole in cross-section because it provides a method of selecting the neutrons which have this very low cross-section. As an application of this technique see Blair and Wallace.[26]

The knowledge of this dependence of cross-section on sample thickness led to a useful conclusion in the measurements of molybdenum.

II - 3 Measurement of the Background.

1. Nature of the Neutron Background.

The background of neutrons as counted by the counter used in the transmission measurements is due to the neutrons being scattered into it. These neutrons do not come directly to the counter but come by a path outside the cone which is formed by the solid angle between the spot source of neutrons and the face of the counter. The laboratory floor is the chief contributer to this scattering but other material in the vicinity and the walls of the building add to the background. The background neutrons are scattered, several times in many cases, and are reduced in energy correspondingly.

The neutrons from the lithium target[8] emerge in all directions and are reflected and then pass through the counter. They constitute a background since they are not in the direct beam to the counter and are not effected by the scattering sample.

Since the background neutrons approach thermal energies during their scattering, in order to reduce the background the counter was wrapped in cadmium and surrounded with boron carbide on all sides except the end facing the source of neutrons. This utilizes

the large absorption cross-section of cadmium^{27} and boron^{27} for low energy neutrons.

The direct neutrons fall on the end of the counter tube and that area is the effective area of the counter in the measurements. The side area of the counter is presented to the background neutrons and the measurement of these neutrons is proportional to this area. It was necessary to abandon the long counter and construct the short counter to avoid a large background.

2. Measurement of the Background.

The method of measuring the background due to the neutrons which come indirectly to the counter was to fill the solid angle to avoid any direct neutron counting by preventing the neutrons from going directly to the counter. For this purpose, a right circular cone was constructed which just filled the solid angle. The cone was paraffin poured in an aluminum foil rolled to the proper shape. The cone was cut off at each end. The small end just covered the spot source of neutrons at the target and the large end just covered the face of the counter.

The large end was covered with a layer of cadmium about 1/8 inch thick to stop thermal neutrons. This

was implemented in a latter cone by a 1/2 inch of boron carbide in addition to the cadmium. In this case there was no additional reduction in the counting rate, thus both cones were considered adequate for the purpose.

An additional cone of twice the length was made for use in the background measurements in the back angle measurements. This longer cone was used at the zero degree position to verify the background measurements. The counter was backed away to twice the normal distance from the target and the longer cone used between the target and the detector. As was expected, the background rate was reduced by a factor of $1/r^2$ since the solid angle was changed by that amount. The proper installation of a Van de Graaff requires a floor remote from the target to lessen the background.

The cone used in the forward direction was 12 inches long. In order to determine its effectiveness in stopping the neutrons the following calculation was made to indicate the number of mean-free paths in the paraffin.

$\sigma_T^A \simeq 10$ barns[27] (Average from 0.1 to 1.0 mev for hydrogen) atomic cross-section

$\lambda_T = \frac{1}{\sigma_T}$ mean-free path

$$\sigma_T = \frac{0.602\ \rho(\sigma_T^A \text{ in barns})}{\text{Mol. Wt.}}$$

$\rho \simeq 1$ for paraffin

Mol. Wt. = 14

$\sigma_T \approx 0.5$ per cm. Macroscopic cross-section

$\lambda_T = 1 / 0.5 = 2$ cm. Mean-free path

For the cone whose length was 12 inches, 30 cm, there were at least 15 mean-free paths. The carbon in the paraffin also contributes to this effect and reduces the mean-free path even more.

3. Variations in the Background.

The background measurements varied from 3 per-cent to 10 percent in the forward direction and from 20 per cent to 23 percent in the back angle measurements. There is an increase in the background in the region of 500 kev neutrons due to the resonance in the lithium target yield at this energy. The increase in background is not completely off set by the faster counting time.

Because the background varies smoothly with energy it was not necessary to measure it each time the machine energy was changed. Since the time involved is large for such measurements they substantially increase the time required to obtain the data. A plot of the

background rate as a function of machine energy and monitor counts was made, and the intermediate points at which data were taken were interpolated. The background rate was checked on each repeatition of the energy setting of previous background measurements and at intermediate points. The checks established the validity of this method of obtaining the background used throughout the measurements.

II - f Scattering-in Correction

1. Meaning of Scattering-in

A scattering sample which is so large that it more than fills the solid angle formed by the detector from the spot source of neutrons causes an error in the measurements. The material beyond the solid angle is also in the beam of neutrons and reacts to the neutron flux just as the rest of the sample. This is principally scattering at the energies of these measurements and some of this scattering is in a direction to carry the neutrons into the detector. These neutrons would not have been counted if the sample were of a smaller size and thus constitute an error in the data. This error is called the scattering-in error.

The data had to be corrected to account for this, the correction is called the scattering-in correction.

2. Calculation of the Scattering-in Correction

The scattering-in correction may be calculated in several ways which give the same result. The method used in this work was suggested by A. Wattenberg and some time latter appeared in the literature in an article by Jones[28].

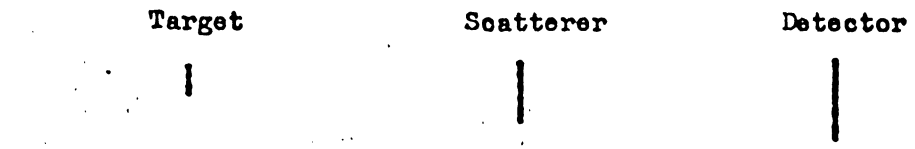
The calculations are based on the following

assumptions:

a. The scattering takes place only once in the sample.

b. The solid angles calculated on the basis of a point source and a point sample are adequate. This calculation was done in detail at Los Alamos by numerical integration over the entire area of the source or the sample. There is no substantial difference between the results of the detailed calculation and the method used here.

The calculation is :



N_o is the counting rate

Q is the strength of the source

k is the efficiency of the detector

N_s is the counting rate from the sample

W_{TD} is the solid angle of the detector from the target

W_{TS} is the solid angle of the scatter from the target

W_{SD} is the solid angle of the detector from the scatterer

f is the form factor (1 for spherical symmeterical scattering).

$$N_o = W_{TD}\ Q\ k$$

$$N_s = W_{TD}\ Q\ k\ e^{-n\sigma} + W_{TS}\ Q\ (1 - e^{-n\sigma})\ W_{SD}\ f\ k$$

$$T_{measured} = \frac{N_s}{N_o} = \frac{e^{-n\sigma} W_{TD}\ Q\ k + W_{TS}\ Q\ (1-e^{-n\sigma})\ W_{SD}\ f\ k}{W_{TD}\ Q\ k}$$

$$= e^{-n\sigma} + \left(\frac{W_{TS}\ W_{SD}\ (1 - e^{-n\sigma})\ f}{W_{TD}} \right)$$

$$= e^{-n\sigma} \left(1 - \frac{W_{TS}}{W_{TD}} \frac{W_{SD}}{} f \right) + \frac{W_{TS}\ W_{SD}\ f}{W_{TD}}$$

Let the right hand term in the above equation be b.

$$T_{measured} = e^{-n\sigma} (1 - b) + b$$

Thus $$e^{-n\sigma} = \frac{T_{measured} - b}{1 - b}$$

To reduce the computation in cases where b is small expand the term.

$$\frac{1}{1 - b} = 1 + b + b^2 + b^3 + \cdots$$

then $$e^{-n\sigma} \approx T - (1 - T)\ b.$$

3. The Magnitude of the Scattering-in Correction

The magnitude of the scattering-in correction depends upon the size of the sample and its position. The correction for the various cases are tabulated below. In the case of the cobalt and manganese samples the correction is a large factor since it is seen in the cross-section as the logarithm.

Scattering-in Correction

	Zero Degree			120 Degree		
	T	b	$\frac{T-b}{1-b}$	T	b	$\frac{T-b}{1-b}$
Vanadium	.60	.0155	.5938			
Manganese	.60	.0625	.5725	.60	.0145	.5941
Cobalt	.60	.0625	.5725	.60	.0145	.5941
Columbium	.60	.0155	.5938			
Cerium	.60	.0155	.5938			

Blair and Wallace[26] calculated the scattering-in correction when they completed the measurements on vanadium in a different manner. A detailed comparison of their correction and the above showed the same results.

II - g Initial Results

1. Range of the Data

The initial results include the total neutron cross-section of vanadium, manganese, cobalt, columbium, and cerium. These measurements were taken immediately after the completion of the Van de Graaff to the point where it could be used for measurements. At this time, September 1949, the machine was limited in the maximum energy of steady operation. This limit of about 2500 kev protons, or the corresponding limit of 750 kev neutrons established the upper limit of the data. Limited time prevented the measurements in the range of neutron energies below 200 kev and in the back angle measurements below 130 kev.

The points were taken to cover the range available and with the intention of filling in the spaces between the points. Actually the resolution due to a thin target, 10 kev, is much too great to permit the interpolation of the points between those measured. If it had been intended to do just the survey work, a thicker target would have been used. The thicker target would have averaged the cross-section and reduced the counting time by giving a larger yield of neutrons.

2. Value of the Data

This data is of considerable value and was made available to the other activities of the Atomic Energy Commission by being included in the Argonne National Laboratory progress report[24]. The value and interest in the total neutron cross-sections of vanadium, manganese and cobalt particularily caused their measurement to be the first task of the Van de Graaff. Since the data for manganese and cobalt was taken in more detail these will be considered in the next section.

3. Total Neutron Cross-section of Vanadium

The total neutron cross-section of vanadium fluctuates rapidly between 200 kev and 700 kev as seen in the attached curve, Fig. 10. The cross-section is about 5.5 barns in the region of neutron energy of 250 kev and decreases to about 3.5 barns at 700 kev. The points represent a statistical accuracy of about 5 per cent in cross-section and an accuracy in energy of $\pm$ 8 kev.

This work was completed by Blair and Wallace[26] and a study of their work indicates that these points are confirmed by their independent measurements. It should be pointed out that they used the same experimental setup and counter and thus any systemmatic errors

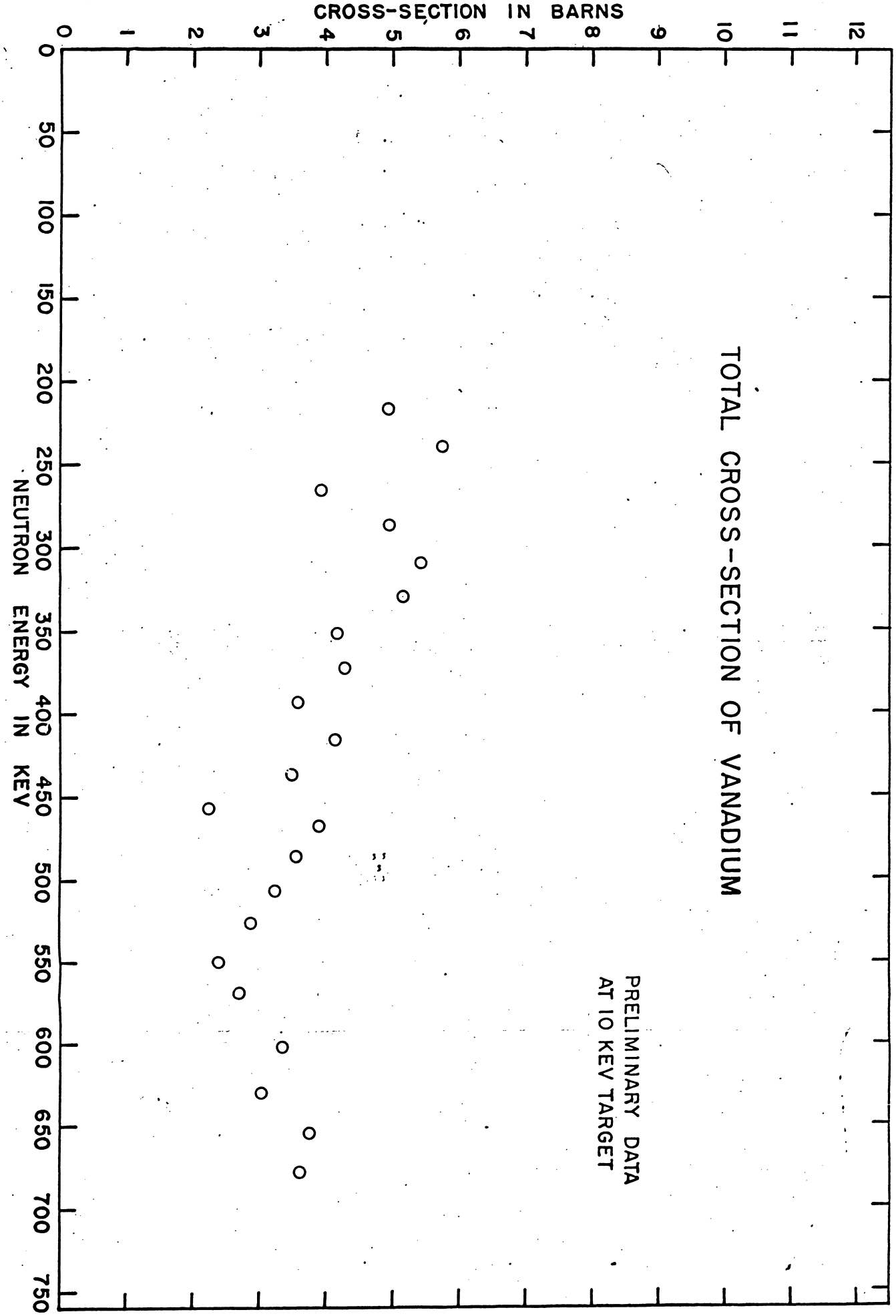


Fig. 10 Vanadium

in these measurements may have also been carried into the work of Blair and Wallace.

4. Total Neutron Cross-Section of Columbium

The total neutron cross-section of columbium, Fig. 11, decreases uniformly from 10 barns at 200 kev to about 8.5 barns at 750 kev neutron energy. The variations are small being about 10 per cent in this region. The energy resolution for these points is ±8 kev and the statistical accuracy is about 5 per cent in cross-section. Note the average value of this cross-section is much higher than that above. This point will be discussed in the conclusions.

5. Total Neutron Cross-section of Cerium

The total neutron cross-section of cerium, Fig. 12, is about 5 barns at 200 kev neutron energy and increases slowly to an average of about 7 barns at 700 kev neutrons. The cross-section fluctuates rapidly at the region of 250 kev neutrons with a variation of 15 per cent. This increase in cross-section with neutron energy is an interesting point since it is expected that the cross-section decreases with an increase in neutron energy. However, the data is not complete enough, particularly in range, to come to any definite conclusion about this behavior, although for a nucleus of this mass one expects the reduction to be evident in this range.

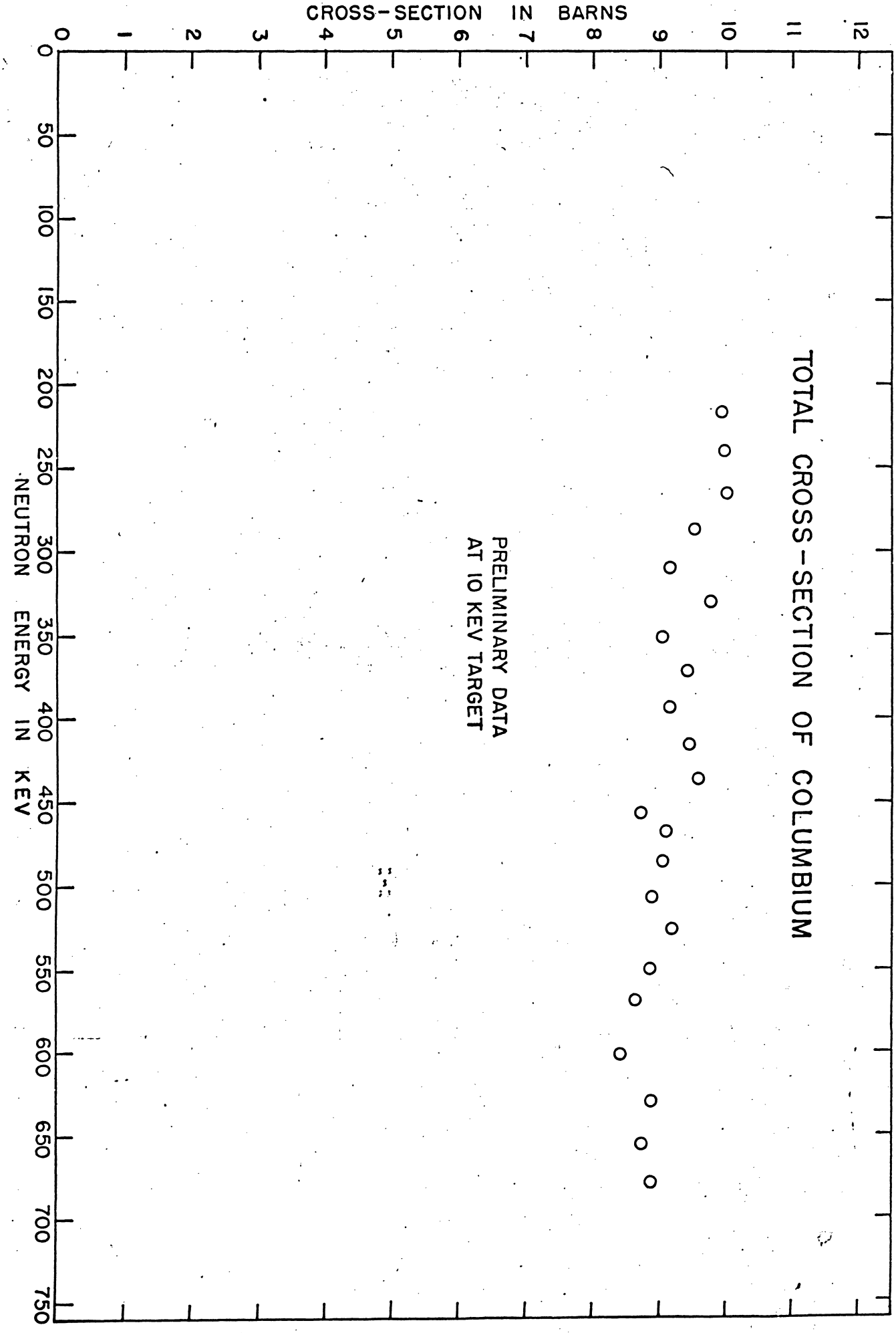


Fig. 11. Columbium

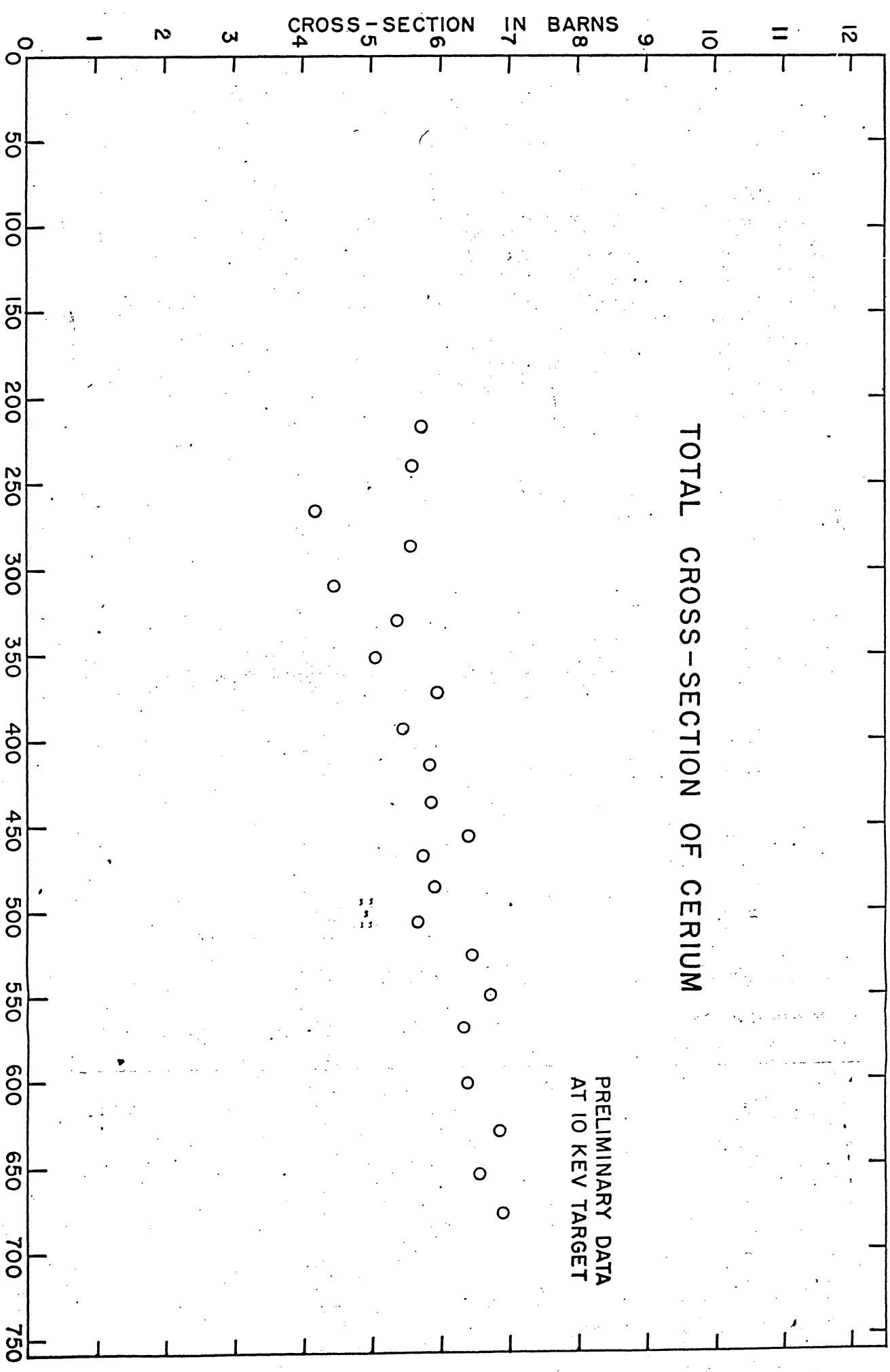


Fig. 12. Cerium

II - h Final Results

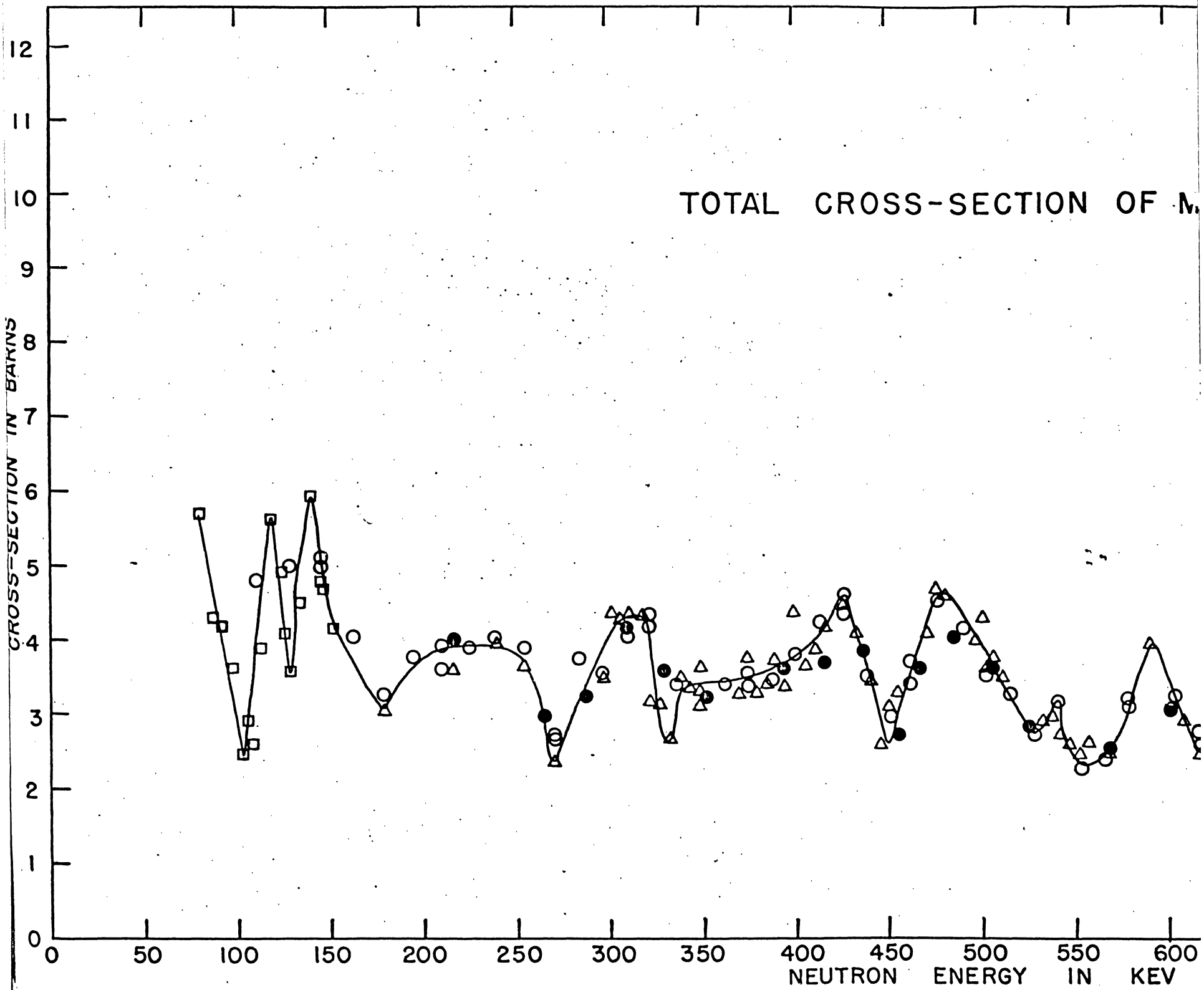
1. Measuring the Detailed Cross-section

The last week in December 1949 and the first week in January 1950 were used to obtain the final detailed data on manganese and cobalt. This work followed the preliminary measurements by about four months during which time the Van de Graaff was improved to permit steady operation at higher energies. The measurements were with a 5 kev target and were made in the following manner. The data were taken at points about 25 kev apart and then the spaces were filled in at intervals of about 5 kev apart. The latter measurements were made with new lithium targets and are indicated by different symbols. Points of interest or where the data was not confirming were run over several times to indicate the true structure, if it could be resolved.

The initial data fit the detailed data over the entire range of the earlier measurements. The data shows the impossibility of interpolating for intermediate points from the initial data.

2. The Total Neutron Cross-section for Manganese.

The total neutron cross-section of manganese, Fig. 13, is seen to fluctuate quite rapidly in the region from


TOTAL CROSS-SECTION OF M
CROSS-SECTION IN BARNS
0
1
2
3
4
5
6
7
8
9
10
11
12
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50
100
150
200
250
300
350
400
450
500
550
600
NEUTRON ENERGY IN KEV

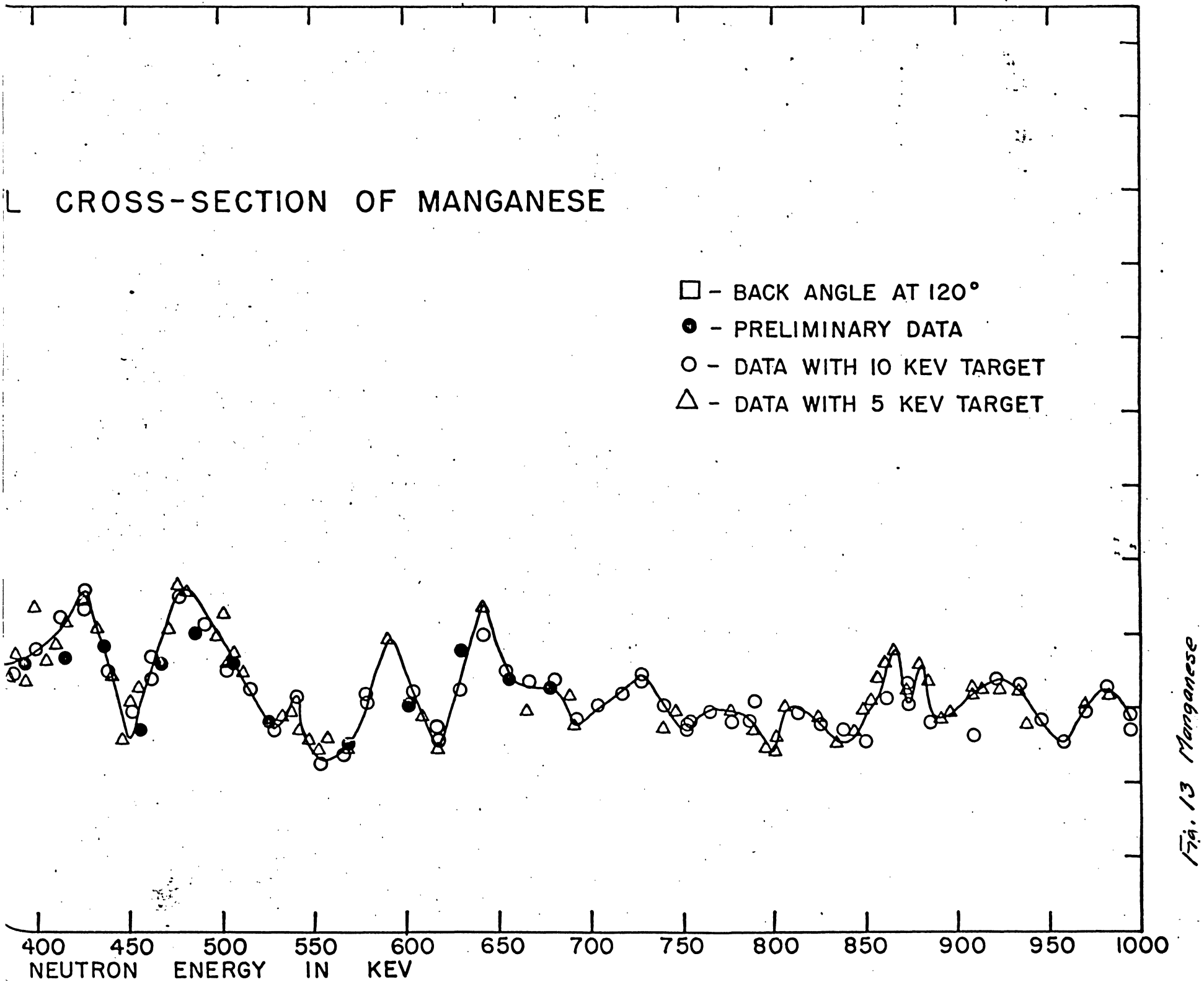


Fig. 13 Manganese

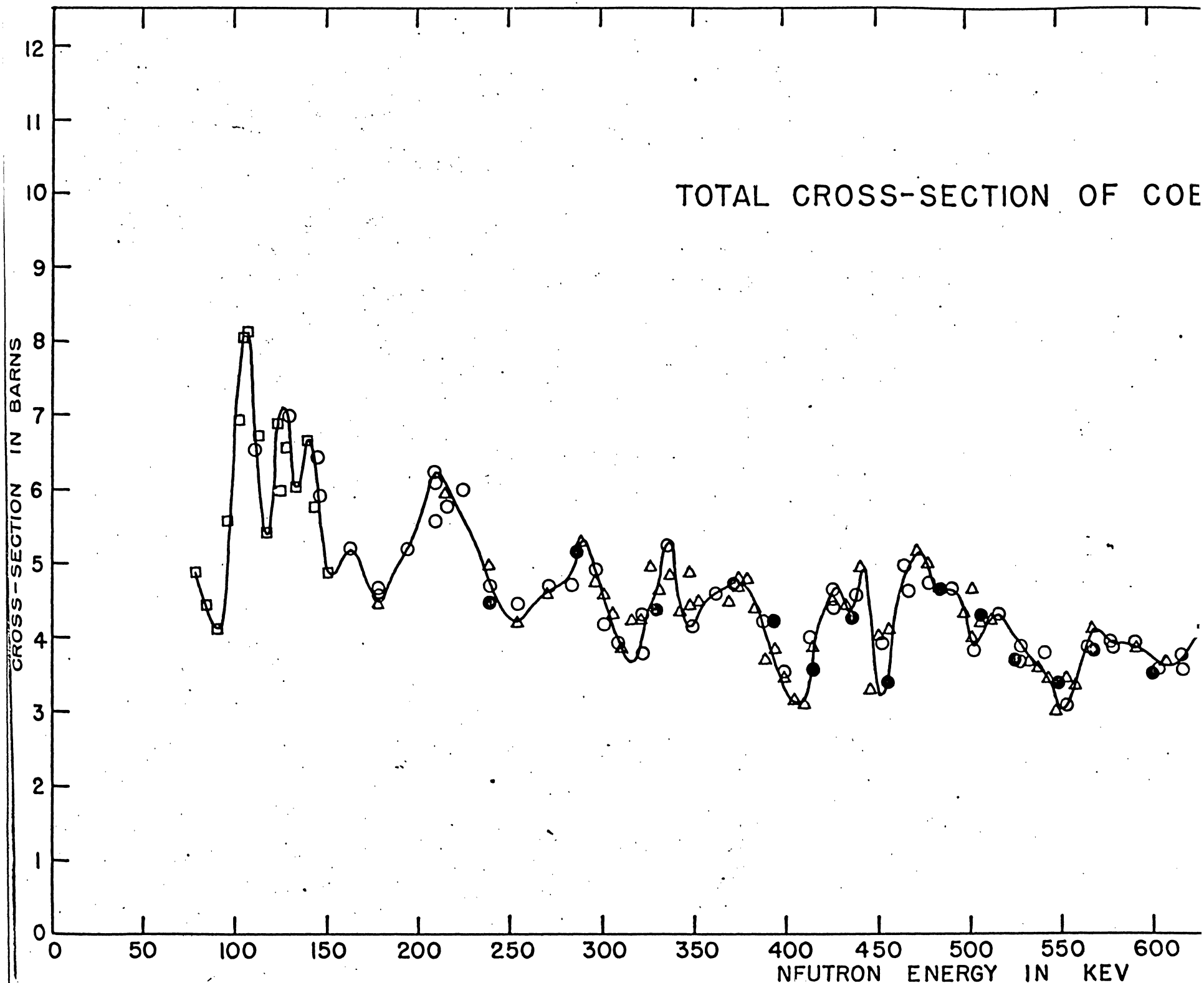
region from 80 kev to 200 kev and at various regions beyond. The fluctuations become less at higher energies and the cross-section gradually decreases from its average of 4 barns at the low energies to about 3 barns at 1.0 mev. The energy resolution is seen to be good enough to resolve the structure in most places. The failure to resolve the structure at all points is discussed below. The energy resolution of this data is ±6 kev and the statistical accuracy in cross-section is greater than 5 per cent.

3. The Total Neutron Cross-Section for Cobalt

The total neutron cross-section for cobalt is of the same nature as that for manganese and is seen in Fig. 14. The cross-section fluctuates quite rapidly at the low energies and decreases slowly to the more uniform values at the higher energies. The cross-section is about 6 barns at 100 kev and decreases to about 3 barns at 1.0 mev. This data is accurate in energy to ±6 kev and statistically accurate to at least 5 per cent in cross-section.

4. Agreement with Vanadium

The curve for vanadium is not available for inclusion


TOTAL CROSS-SECTION OF COE
CROSS-SECTION IN BARNS
0
1
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300
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400
450
500
550
600
NFUTRON ENERGY IN KEV

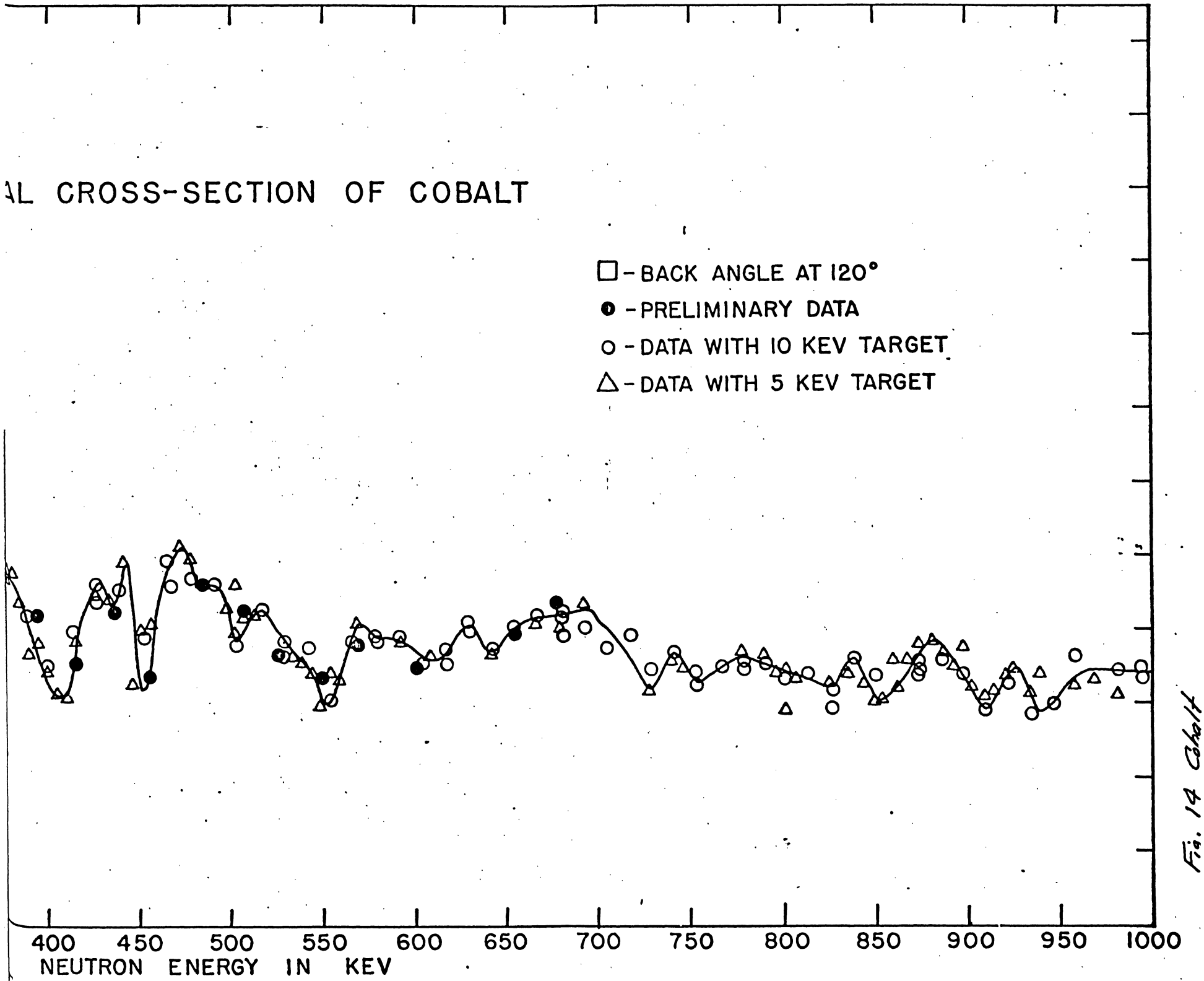


Fig. 14 Cobalt

in this thesis but may be seen in the paper of Blair and Wallace,[26] or in a compilation of cross-sections by Adair[14]. The agreement between the cross-sections of vanadium and those of cobalt and manganese is close in general and the differences are in detail. The general agreement is anticipated and present. It is believed the data confirms the basic similarity of the nuclei of these three elements.

The failure to observe the holes in the cross-sections of cobalt and manganese, such as were found in vanadium[26], may be due to two factors. Either they do not exist or the energy resolution of these measurements do not allow the resolution of the points of very low cross-section. Perhaps a more detailed search would reveal them.

5. Resolution of the Structure.

The number of points that were taken in this work were many more than had been anticipated and used up the available time quite rapidly. For this reason the back angle work was not carried to the lower energies that were intended. The number of points were increased when it was found that in repeating the data, both at the exact same energy points and intermediate points, the structure was not easily resolved. These points

were supplemented by others in the region to trace out the true nature of the cross-section as a function of neutron energy.

The structure could not be resolved over the entire range of neutron energy. This is true at high neutron energies, where according to theory[30], the resonance level density increases and the measurement method averages the contributions of many resonances. This effect is also seen to occur in the cross-section of manganese at neutron energies from 350 to 430 kev. The resonance level density is less at low neutron energies and the resolution of the resonances there is possible.

6. Failure to Observe the 10 per cent Yield of Neutrons

The 10 per cent yield of neutrons[22] from the lithium target above the primary neutron energy of 650 kev is not obvious in these curves. The low energy structure is not identifiable in the region beyond 650 kev neutrons, thus no effort was made to extract it.

PART III MEASUREMENT OF THE TOTAL NEUTRON CROSS-SECTION OF MOLYDENUM

III - a Introduction

1. Reasons for Measuring Molybdenum

The measurement of the total neutron cross-section of molybdenum was undertaken for several reasons, the two most important of which are as follows. Firstly, the information was desired by those involved in neutron reactor design and calculations. Secondly, it represented a measurement which could be done in the limited time available to me. This work was done in the summer of 1950 within a period of two weeks. The experience obtained in the construction of the Van de Graaff and the measurements described earlier made it possible for the work to be done in the time available.

The naturally occuring molybdenum has many isotopes of the same relative abundance[11]. For this reason the resolution of any resonance structure is not expected.

Isotope	Isotopic Abundance
Mo^{92}	15.86
Mo^{94}	9.12
Mo^{95}	15.7
Mo^{96}	16.5
Mo^{97}	9.45
Mo^{98}	23.75

2. Difference Between This and the Earlier Measurements

The fundamental difference between this work and that described earlier is the method of detection of the neutrons. The difference is so great and unique that this method constitutes a new approach to the measurement of total neutron cross-sections.

In these measurements the detector[29] consisted of a group of counters well shielded by a massive shield in contrast to the earlier measurements with a single detector with very little shielding. The shield results in independence of the data on any scattering-in, and results in a very favorable background ratio.

The neutrons were produced in the same reaction, Li(p,n)Be, as before and under the same operating conditions on the Van de Graaff. The comments made earlier on the production of neutrons and their energy spread hold exactly in these measurements on molybdenum. The statistical considerations are the same and will not be discussed again.

III - b Description of the Detector

1. Description of the Counter Arrangement

The detector[29] used in these measurements consisted of nine BF_3 counters each in seven concentric circles embedded in paraffin. These rings of counters were surrounded by a very effective shield. The arrangement is shown in Fig. 15. The neutron beam was collimated by the tapered hole as shown and was scattered into the counters by a cylinder of paraffin placed accurately at the geometrical center of the counter assembly.

The shield consisted of many different elements and moderating materials placed in pans and arranged in the form of a series of discs which formed the conical nose of the shield. The material around the barrel of the assembly was boron carbide mixed with a high melting paraffin. The shielding was quite good and reduced the background count to about 1 per cent in the measurements at zero degrees and to not more than 2 per cent at the 120 degree position used in the back angle work.

2. Purpose of the Detector

The detector was designed and built for use in the measurement of the neutron scattering cross-section.

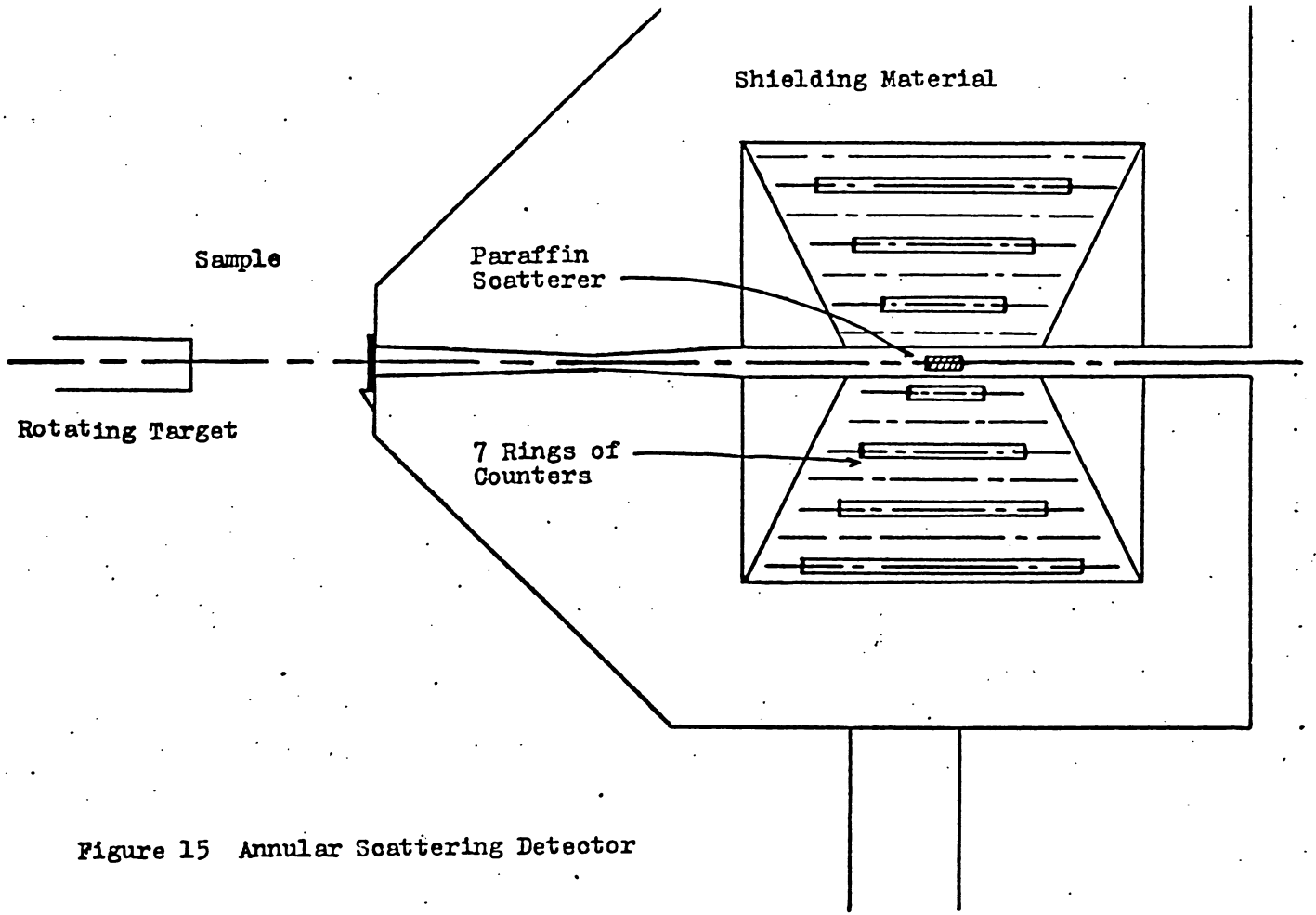


Figure 15 Annular Scattering Detector

The several rings of counters were to separate the neutrons of different age, i.e., different diffusion lengths, which is a measure of their energy. This age information is to be analysed to learn the amount of energy lost in an inelastic scattering event. The instrument has a great advantage in the measurement of total neutron cross-section since the amount of material required may be reduced to much less than in the open scattering method. The use of self protection or self detection techniques is planned for this detector.

Another advantage of this arrangement is the efficiency of counting. The time required for obtaining a desired number of counts is much less with this detector than the detector used in the measurements on cobalt and manganese. The ratio of counting time to obtain the same number of counts between the two methods is more than 5 to one in favor of the shielded detector when the same target thickness is used.

The sample was supported by a small angle bracket in which the sample rested against the front of the shield and concentricly with the collimating hole.

3. Scattering-in

The scattering-in correction was not required in this work because only the neutrons which could enter

into the detector are those which strike the part of the sample covering the opening into the collimating hole. The material of the sample which extends beyond this hole can not scatter neutrons into the detector because of the excellent shielding. The size of the sample and its shape, other than the requirement of parallel faces, are unimportant, if it is large enough to cover the hole completely. This permits the samples to be quite small and requires a minimum of material for transmission measurements and even less material for scattering measurements.

4. Use of a Monitor Counter

Since the sample added very little mass to the massive shield, the scattering of the sample did not add appreciably to the scattering due to the massive shield. Thus the scattered neutrons were uneffected by the sample and the use of a monitor in the form of a neutron counter was possible. The monitor counter was placed at 30 degrees from the proton beam.

The monitor consisted of a long neutron counter, 10 inches, embedded in a mass of paraffin. The monitor was placed close enough to the spot source of neutrons to receive the same number of counts as the sum of the

counters in the detector. Thus the statistical errors were as small as possible for the counting interval.

5. Difficulties with the Counters

The detector was new and the troubles it had were associated with the newness. The counters would give spurious counts occasionally. The efforts to eliminate this difficulty resulted in removing some of the troublesome counters from the rings and in not using the outer rings at all. The data were taken, for the most part, by the three sets of inner rings of counters. The high counting efficiency permitted this without too great a sacrifice of counting time. The inner rings were more active in counting than the outer ones because of the neutron density variation inversely with distance from the scattering cylinder at the geometrical center of the counter assembly.

6. Back Angle Work

For the back angle work the entire detector was pivoted about a point directly beneath the lithium target to an angle of 120 degrees in the laboratory system from the proton beam. The massive detector had rollers to permit this shifting and leveling platesto anchor it in place securely. The distance from the source to the detector is the same in both the 0 degree

and the 120 degree work.

7. Measurement of Background

The measurement of background is accomplished by removing the paraffin scattering cylinder from the center of the counter assembly and allowing the collimated neutrons to pass on through the detector. In this case the counting is due to scattered neutrons which get through the shielding or due to air scattering in the collimating tube. This represents a background which is subtracted from the data. The background is about 1 per cent in the zero degree measurements and about 2 per cent in the back angle work.

8. Additional Considerations

The time between the switching of the count switch and the dropping of the shutter was used as a check for spurious counts. Other checks were used as before.

The energy range of 10 to 1230 kev reflects the improvement in the operation of the Van de Graaff due to its use and the changes made on it during this time between the earlier measurements and this data. These measurements were about one year after the preliminary measurements described before. The measurements of the cross-section at neutron energies of less

than 130 kev were made in the back angle of 120 degrees in the laboratory system.

The scalars used in this work were equipped with decade scales rather than binary scales of the earlier scalars. This speeded the measurements by making the interpolation of the counts easier. The counts from several rings were added together to obtain the sum of at least 10,000 counts for each measurement, excepting the background.

III - c Molybdenum Sample Characteristics

1. Density and Purity

Two molybdenum samples were used in obtaining the data, one of which was less dense than the solid metal due to the presence of cavities in the slug. This is called the error density sample. The discrepancy was found when the density was calculated as a check. The other sample was solid and replaced the error sample in the measurement.

Both samples were shown to be quite pure by a spectro-chemical analysis made by the Chemistry Division of the Argonne National Laboratory. This analysis showed that the total impurities were less than one per cent and no element was present as an impurity more than 0.1 per cent.

The data from the incorrect density sample was matched with the data from the correct density sample at one point in order to have confirming data. This match actually consisted of redetermining the number of atoms per square centimeter for the error sample.

2. Characteristics of the Molybdenum Samples

The samples of molybdenum were obtained from the special materials group and had the following characteristics:

	Correct Density Sample	Error Density Sample
Atomic Number	42	42
Atomic Weight	95.95	95.95
Thickness in cm.	1.063	1.97
Diameter in cm.	2.57	2.77
Weight in grams	54.022	86.467
Atoms per sq. cm.	$.6625 \times 10^{23}$	$.925 \times 10^{23}$ as corrected

III - d Accuracy of the Measurements of Molybdenum

1. Energy Variations

The target thickness in this work was 10 kev. The diameter of the hole into the detector, and thus the effective size of the sample, was 5/8 inch. This results in the solid angle between the spot source on neutrons and the detector of 0.00213 steradians. This is a plane angle of 3 degrees. The variation of the neutron energy over this angle, as obtained from the McKibben chart[1], is 2 kev in the zero angle measurements and 1 kev in the back angle work. The energy stability of the machine as determined from the measurements at threshold is ± 3 kev. The overall accuracy in energy is ± 8 kev for the forward work and ± 8 kev for he back angle work. The statistical accuracy as computed before is 5 per cent. In this work the measurements all were for at least 10,000 counts, excepting the background measurements.

2. Failure to Observe Structure

The failure to resolve any structure is due to the several isotopes of molybdenum and other errors. These other errors are systematic and random and are believed to arise in the detector since the detector is the only fundamental change in the system. In addition,

the spurious counting and other troubles found in the detector prior to the actual measurements lead to placing the responsibility for the large errors on it. The net result was an overall accuracy in cross-section of 10 per cent.

3. Cross-section Dependence on Sample Thickness

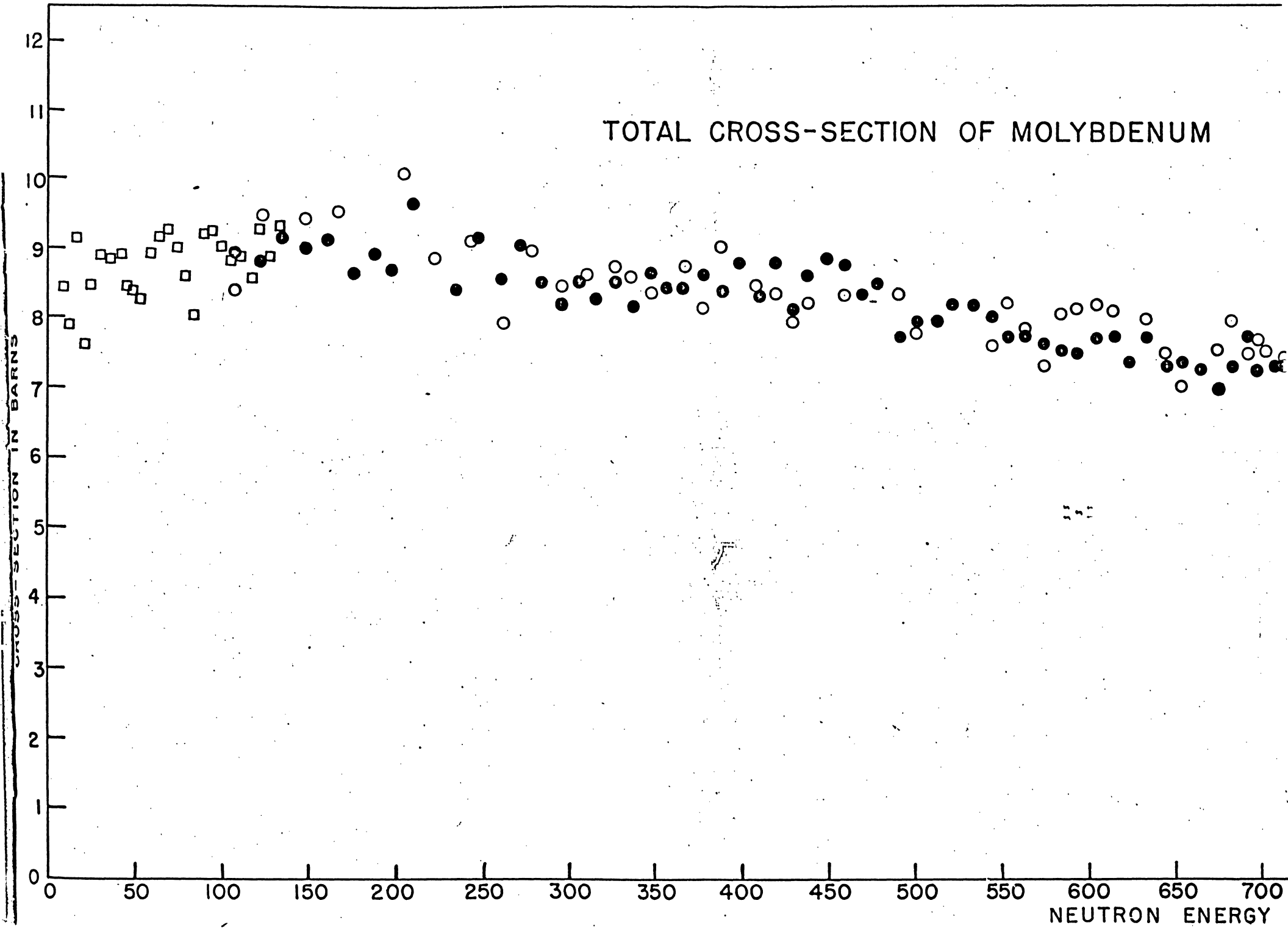
The realization that the errors in the cross-section were greater than the statistical errors indicated, came from the comparison of the cross-section measurements with the thick sample and with the thin sample. If the errors were not so great, then the cross-section measured using the thin sample should be consistently higher than the cross-section measured using the thick sample, by the argument on page 56. Since reference to the data, Fig. 16, shows this not to be true, it must be concluded that the accuracy in cross-section is not that expected from the statistical considerations, but much less.

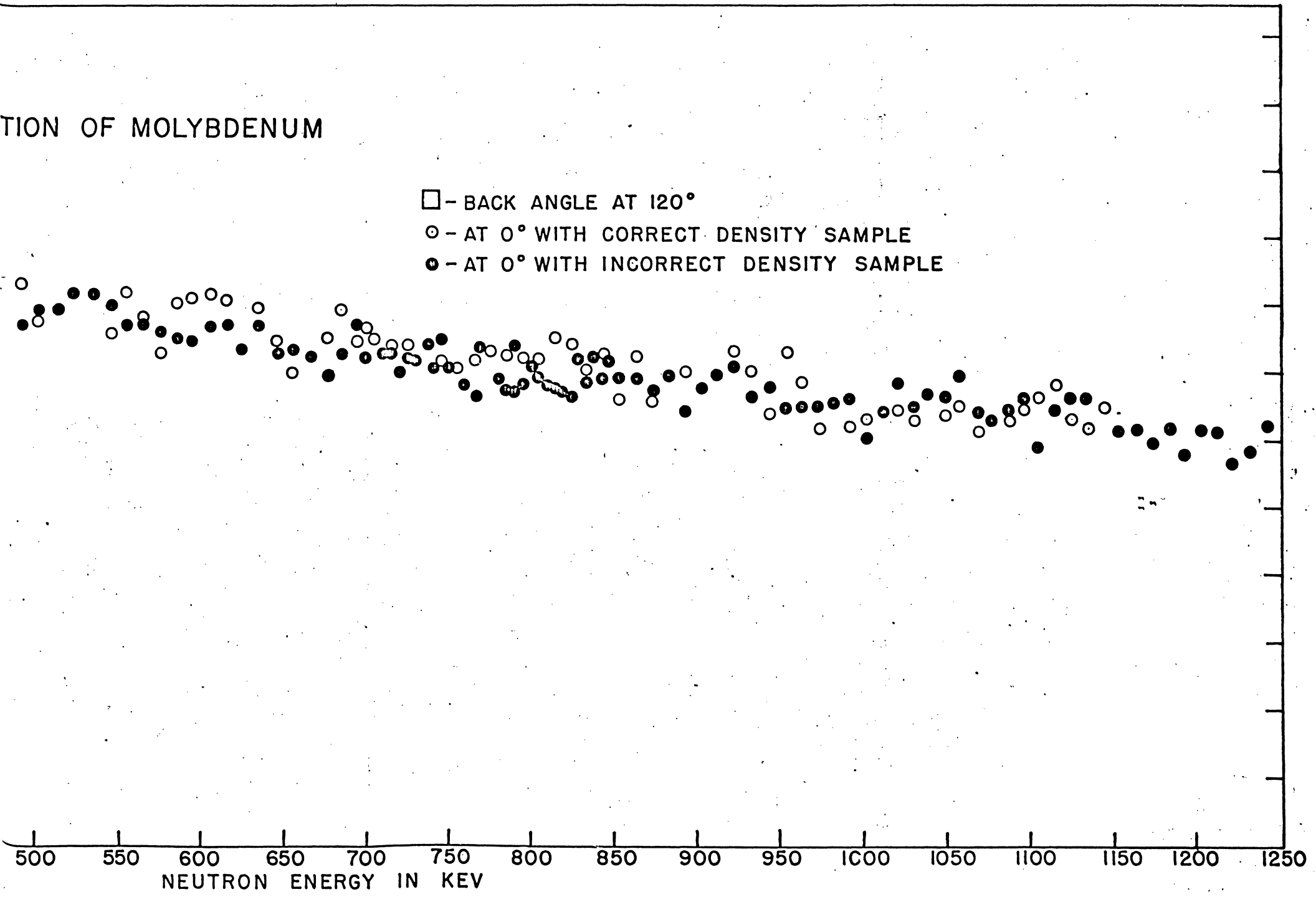
III - e Final Results on Molybdenum

1. The Total Neutron Cross-section for Molybdenum

The total neutron cross-section for molybdenum as seen in Fig. 16 has no structure resolved by these measurements because of the errors in the cross-section measurements and because of the many isotopes present in the samples.

The cross-section is practically constant at 9 barns from the lowest energy measured, 10 kev, to 250 kev. It then decreases slowly and uniformly to 6 barns at 1230 kev.


TOTAL CROSS-SECTION OF MOLYBDENUM
CROSS-SECTION IN BARNS
0
1
2
3
4
5
6
7
8
9
10
11
12
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
NEUTRON ENERGY


TION OF MOLYBDENUM
□ - BACK ANGLE AT 120°
⊙ - AT 0° WITH CORRECT DENSITY SAMPLE
● - AT 0° WITH INCORRECT DENSITY SAMPLE
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
NEUTRON ENERGY IN KEV

CONCLUSIONS

1. Dependence of Fast Neutron Cross-section on Mass Number

A study of neutron cross-section measurements for many elements and at high energies reveal a common characteristic. It is seen that the total cross-section, which at the high energy is primarily scattering, for each element reaches a constant value which is given by;

$$\sigma = 2\pi(1.5 \times 10^{-13})^2 \quad A^{2/3}$$

where A is the mass number of the element or isotope, and σ is the neutron cross-section at very high energies.

This effect occurs when the neutron size, i.e., the De Broglie wave length, $\lambda = h/p$, is small compared to the size of the nucleus. In the above, h is Plank's constant, $(6.62363 \pm 0.00016) \times 10^{-27}$ erg seconds, and p is the momentum of the neutron. Heavier nuclei reach this region at lower energies than the light nuclei. This rule is not useful in the range of neutron energies where the relation between neutron size and nucleus size is not as above.

The following table shows the value of the cross-section of the various elements measured at the highest energy for each.

	Maximum Energy in kev.	Measured Cross-section	Calculated Cross- section
Vanadium	700	3 barns	1.95 barns
Manganese	1000	3	2.05
Cobalt	1000	3	2.15
Columbium	700	9	2.92
Cerium	700	7	3.83
Molybdenum	1230	6	2.97

These values do not agree closely but, in the cases where the maximum energy is 1 mev or higher, it may be seen that the curves may be extropolated to the limit value. Failure for more agreement is caused by the limited range in energy.

2. Cross-section Dependence on Mass Number at Particular Energies

A study of the neutron cross-sections of all elements at a specific energy reveals an orderly, but not linear, dependence[31] on the mass number of the element. Fig. 17 shows this curve for the measurements available[14,27] at an energy of 750 kev. Agreement with this distribution is a useful confirmation of the data and permits the prediction of unmeasured cross-sections. The following table lists the values predicted for the elements measured here and their measured values. The measurements which were terminated at 700 kev have been extrapolated to 750 kev.

	Measured Cross-section at 750 kev	Cross-section from curve at 750 kev
Vanadium	3 barns[26]	3 barns
Manganese	3	3
Cobalt	4	3.4
Columbium	9	8
Cerium	7	7 (extrapolated)
Molybdenum	7.	8

It is believed that the agreement shown here is not coincidental. The values used in plotting the curve are the average value or that which would be obtained with a thick target. More study is required to determine the full value of this information.

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