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THE CONSTRUCTION OF A FERMI NEUTRON CHOPPER FOR CROSS SECTION MEASUREMENTS

by

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A

THESIS

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Approved by

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ABSTRACT

A Fermi neutron chopper and control system has been constructed and put into operation at the end of the UMR Reactor thermal column.

The operation of the chopper has been demonstrated by reproducing the slow neutron cross section data for aluminum and by measuring the previously undetermined slow cross section of cobalt.

The chopper which is powered by a series DC motor consists of 34 cadmium plated stainless steel blades separated by 1/16 inch aluminum spacers. The design incorporates the better characteristics of the Brookhaven and Argonne slow choppers. Speed regulation is accomplished using a silicon controlled rectifier feed back system which permits speeds from 50 to 15,000 rpm. The speed variation at all speeds is less than one percent.

Aluminum cross sections in an energy range from 0.006 to 0.08 eV were shown to duplicate the Argonne results except for one additional peak which appeared at about 0.02 eV. Additional investigation is planned to explain this peak.

Cobalt cross sections were determined as a function of energy from 0.005 to 0.1 eV. These data are believed to be the first published for cobalt in this energy range.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

The major purpose of this thesis is the design and construction of a Fermi (slow) neutron chopper using modern detection methods. Therefore, a significant portion of this paper is allotted for the purpose of describing the chopper, its instrumentation, and its experimental significance. A secondary purpose for this work is to demonstrate the usefulness of the neutron chopper by measuring a previously undetermined neutron cross section.

This work includes the measured cross sections of cobalt as a function of energy from 0.005 eV to 0.1 eV. This is a significant energy range in the construction of low temperature thermal reactors because the most probable thermal neutron at 20°C corresponds to 0.025 eV. A literature survey revealed that the total cross section of cobalt had not been reported for the low energy range from 0.005 to 0.03 eV.

Aluminum cross sections were also measured as a means of standardizing the energy determination by making reference to the known peaks in the aluminum cross section.

II. LITERATURE REVIEW

Neutron choppers can be separated into at least two distinct groups, fast choppers and slow choppers. Fast choppers are designed for the purpose of pulsing a beam of high energy neutrons above the cadmium cutoff region while the latter is designed for pulsing (or velocity selection purposes) in the thermal neutron region. The high neutron flux available in reactors opens the possibility of high resolution measurements of neutron velocities by timing the neutrons electronically as they move over a particular length of path. These time of flight methods of velocity selection were developed (1,2) principally in connection with pulsed cyclotron neutron sources. However, the techniques involved have been employed directly for use with neutrons produced by reactors (3). In the time of flight method, a burst of neutrons on the order of several microseconds duration is produced and the time required for the neutron to reach the detector some distance away is measured electronically (4).

The general principles involved in the velocity selection are the same whether the bursts are produced by a modulated cyclotron or a neutron chopper operating on a reactor. The following simple relations hold for the energy, velocity, and the time of flight over a one meter path. The velocity of a particular neutron over a one meter path length is given by (4)

$$V = 10^6/t$$

The energy in electron volts is given by

$$E = 51.5 \times 10^2/t^2$$

$$t = 71.5/\sqrt{E}$$

Where:

t = time in micro-seconds
E = energy in eV
V = Velocity in m/sec

The resolution in velocity and energy is given by

$$\Delta V = \frac{-10^6 \ \Delta t}{t^2} = - 10^{-6} V^2 \ \Delta t$$

$$\Delta E = - \cdot 028 \ E^{3/2} \ \Delta t$$

The shape of the neutron burst function and that of the counter have been handled differently by several sources (3,4,5). Indeed this shape would vary with the type and design of the chopper and with its detection equipment. It is generally agreed, however, that the actual shape can be replaced by an equivalent triangle in order to simplify calculations (23). The chopper can not produce a pure knife edge effect because of its physical size. Therefore, there is always some departure from the ideal square pulse.

The total time of flight of the slowest neutron in a channel is given by (5)

$$t_s = 1/2\ T_n + t + T$$

Where:

T_n = Burst duration

t = Opening time of a channel

T = Time the gate remains open

While the time of flight for the fastest neutron is

$$t_f = t - 1/2\ T_n$$

Therefore the velocity range in a particular channel is found to be

$$\Delta V = V_f - V_s = \frac{L}{t - 1/2\ T_n} - \frac{L}{t + T + 1/2\ T_n}$$

Where:

L = Path length

V_f = Velocity of fastest neutron

V_s = Velocity of slowest neutron

For any given chopper operating at a rotational given speed ω, there exists a minimum neutron velocity which is transmitted without attenuation. This most favored velocity is given by $4\omega R^2/s$.

For neutrons of velocity $V > 4\omega R^2/s$,

$$T_n = s/\omega R$$

Where:

R = Radius of rotation

s = Spacing between plates

But when V is less than this most favored velocity,

$$T_n = 4 \sqrt{s/\omega V} - 4 R/V$$

The Fermi Chopper is designed primarily for the production of neutron bursts while the actual velocity selection is performed by an electronic timing (4). Electronic timing has been accomplished (4) by a series of photo cells activated by a rotating beam of light which actuates several counters as a function of time. Later innovations have made use of the multichannel analyser operating in the time mode (5).

Other types of choppers called velocity selectors have been developed by Dunning et al (6), by Ringo (7), and Wollan (8). The purpose of the velocity selector is not only to pulse the beam of neutrons but also to act as a mechanical monochromator to select a narrow band of neutron energies while rejecting all others.

A mechanical monochromator selects the narrow band of velocities with no time of flight measurements involved. Monochromators have certain advantages over a time of flight instrument. For example, activation with mono-energetic neutrons can be accomplished with the monochromator and is impossible with the time of flight method (9). The monochromator is at a disadvantage concerning cross section measurements in that only one velocity can be studied at a time (4). When used on a low power reactor, choppers are desired over monochromators because of the higher count rate possible (10).

This paper concerns the techniques used in the slow chopper where little or no monochromatization of neutrons results. The energy measurement is performed by electronics on a time of flight basis. The Brookhaven slow chopper (11), designed to contain curved channels, produces some energy selection of neutron bursts. However, the major purpose for the curved plates is to facilitate more efficient transfer of neutrons through the chopper. A slow chopper was used by Fermi at Argonne in 1943 (4), and later his design was incorporated by Brille and Lichtenberger (12) at Argonne. A similar chopper is in use at the Harwell, England Pile (13). The Argonne chopper (using the Fermi design) is made up of alternate layers of cadmium and aluminum sheets driven by an electric motor at speeds up to 180 revolutions per second (2). Crystal-filtered neutrons (8) and lead-filtered neutrons (15) have been used for the purpose of velocity selection. The effect of higher order reflections is negligible in the epithermal region where the crystal monochromator is principally used but is a serious drawback in the use of thermal neutrons. As a result the mechanical velocity selector is preferable for thermal neutron work. Indeed some work has been done using combinations of a crystal-filter and a neutron chopper (14).

One of the principal uses of a neutron chopper is in determining total neutron cross sections (16,17). There are three basic techniques for measuring cross sections: Beam transmission, in pile, and activation (10). In the beam method a beam of neutrons is taken out of the reactor by a thermal column or a beam tube. The neutrons are made to pass through the specimen and the intensity is recorded with or without the specimen. The neutron chopper can be used with the beam method to determine cross section as a function of energy. In the pile method the material is placed in the core and the change in reactivity is measured; in this method only the absorption cross section can be determined. The activation method consists of irradiating a specimen a given time and observing its induced activity. However, because all the absorptions do not produce activity, only the activation cross section is measured.

This work will demonstrate a method for total cross section measurement using the beam transmission method and a neutron chopper. Total cross section can be distinguished from the scattering and absorption cross sections by the counter used (10). A single BF_3 counter tube subtending only a small angle from the specimen would indicate the total cross section while a four pi counter would detect the scattered neutrons and therefore indicate only the absorption cross section.

Total cross section measurements have been achieved through the use of a slow neutron chopper by several investigators (12, 16, 17). The general procedure is to measure the thermal neutron spectrum with the sample in the neutron beam and then to compare this to the thermal neutron spectrum without the sample. Schunk, Randolph and Brugger (18) determined the total cross section of Ti, V, Y, Ta, W, using a slow chopper operating at a speed of 2,100 rpm. A 1024 multichannel time analyser was used as the time energy base. Stone and Slovacek (19) determined the cross sections in the range above the cadmium cutoff using the 2 inch shutter composed of 1/16th inch borated phenoic plates and 1/16th inch aluminum spacers. Cadmium cannot be used as a shutter blade in this region because of its transmission of epithermal neutrons.

The familiar equation (20,21,22) $I = I_o e^{-N\sigma t}$ is derived as follows:

The change in neutron intensity of the passing through thickness dt is

$$dI = -\sigma I N dt$$

$$\int_{I_o}^{I} \frac{dI}{I} = -N \int_{o}^{t} \sigma \, dx$$

$$\frac{I}{Io} = e^{-\sigma Nt}$$

or,

$$\sigma = \frac{-\ln I/Io}{Nt}$$

Where

σ = The total microscopic cross section

N = Number of atoms per cm^3

t = Thickness

Io = The count rate without the sample in the beam

I = The neutron count rate as a function of energy with the sample in the beam

A discrete cross section is then calculated for each energy increment as a function of the time of flight. Hoag (23) describes a classical method for determining total neutron cross section. In this method the log of the transmitted intensity is plotted as a function of the material thickness and the slope of this graph is taken to be the total average cross section.

This method is advantageous because of its simplicity but is limited in that only the average cross section for the energy of the neutrons in the beam can be determined. Total cross sections may be determined by using a crystal spectrometer (24,25). However, the crystal spectrometer has a limited useful energy range of 0.1 to 10 eV because of the loss of intensity on the low end and loss of resolution at higher energies (23). Neutron choppers have the advantage of high energy resolution while still maintaining a relatively high count rate. A slow chopper developed by Fermi as early as 1943, to determine total cross sections at various energies, was later improved by Brill and Lichtenberger (12). The advantage of this type of chopper is the possibility of high energy resolution in the fractional eV range. The Brookhaven chopper using curved blades and wide spacing between the blades (27) was designed to improve the energy resolution in the extreme low fractional eV level. This chopper is capable of measurements of the slow neutron spectrum extending to a wave length of 25Å(4).

III. GENERAL DESIGN FEATURES

The Brookhaven slow chopper (30) was used as a model in designing the present chopper. Many changes were necessary for reasons of compatibility with the UMR Reactor, financial resources, and experimental purpose. The design of the gear box and the light beam mechanism which it controls are identical to the Brookhaven design.

A. Construction Details

This design differs from many choppers(5,23) in that spacing between the blades is accomplished by very narrow strips of aluminum providing a space consisting of about 60% air, while other choppers use solid aluminum as the spacer between the plates. While the aluminum itself has a low cross section it is believed that air spacing is better because of less neutron scattering. Egelstaff (27) estimates that removing 87% of the aluminum reduces the scattering to 10%.

The rotating chopper (Fig. 1) has 34 blades, 3 1/2 x 4 3/4 x 0.16 inches thick which have been cadmium plated to a thickness of .002 inches each side. Sets of five aluminum strips 3 1/2 x 3/8 x 1/16th inch are used as spacers between the blades. This sandwich type structure is held together by 15 steel bolts.

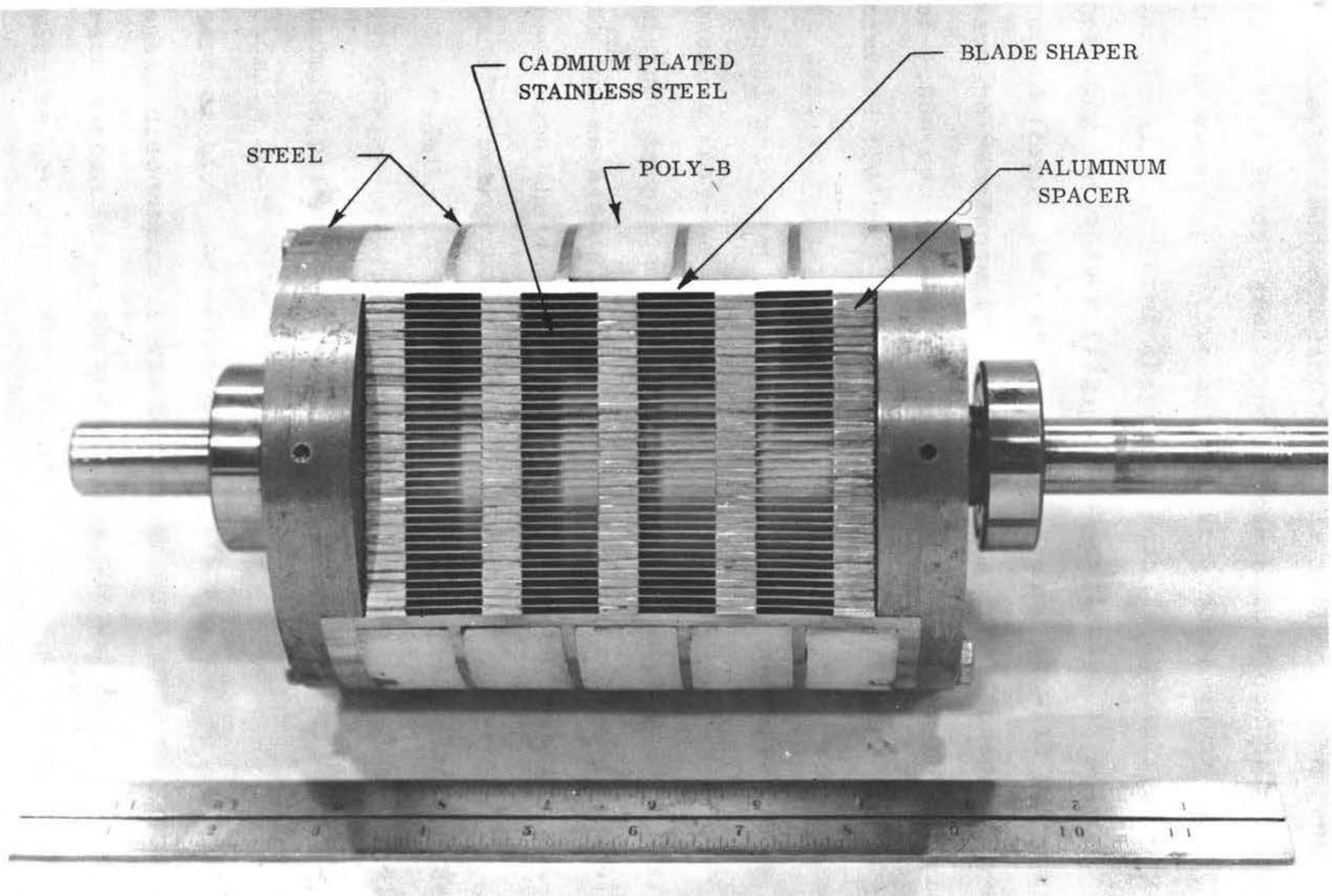


Fig. 1 Neutron Chopper Rotor With Cover Removed

The chopper is of the same general design as the Brookhaven chopper except for the following changes: The rotor is designed so that the blades can be operated in the curved position as used at Brookhaven or as a conventional flat Fermi chopper. This is accomplished by removing the shaper (Fig. 1) and replacing it with a curved form. When this change is made it will be necessary to rebalance the rotor if rotational speeds in excess of 4,000 rpm are to be encountered. A boron-polyethylene mixture (Poly-B) supplied by Reactor Experiments, Inc. is used as a fast neutron shield rather than the conventional polyester-boron mixture. This change was made because Poly-B was commercially available. This boron mixture is placed on the ends of the chopper (See Fig. 1) to act as a shield for high energy neutrons which would penetrate the cadmium plate and thus increase the epicadmium background.

Cadmium is a soft metal which deforms easily under the forces of high rotational speeds. Stainless steel cadmium plated blades are considered superior to pure cadmium because of the increase in strength which is necessary at high operating speeds. This practice also permits small discontinuous spacers to be used between the blades rather than solid sheets of aluminum which would otherwise be necessary for strength. The spacing between cadmium blades is wider than most choppers (5,23) which allows a wider neutron window and thus, in the interest of resolution, requires an increase in rotational speed. This combination is possible because of the high strength materials which have been used in the construction. Strength in materials limits the top speed to about 500 m/sec (27). This particular rotor which is believed to be safe up to 15,000 rpm is covered with a 1/8 inch aluminum sleeve to reduce windage friction (See Fig. 2).

A second rotor, (now under construction) which uses five curved blades with a spacing of 1/2 inch, is designed to increase the intensity of the extreme low energy neutrons. The curved blades have a radius which varies between 5 and 7 inches and are designed to function as a Fermi chopper and act as a crude velocity selector as well. This curved blade chopper operates at a disadvantage because only one burst of neutrons can be used per revolution. However, this is sometimes considered as an advantage particularly in the case of the extremely low velocity neutrons because the duty cycle of the chopper requires a long waiting period after the initial burst (4).

The two rotors described above are designed to be interchangeable for use with the motor and the timing mechanism. The driving motor manufactured by General Electric is rated 1/3 horsepower at 12,000 rpm, with a no load speed of 16,000 rpm. However, because of friction in the recently purchased chopper bearings, a top

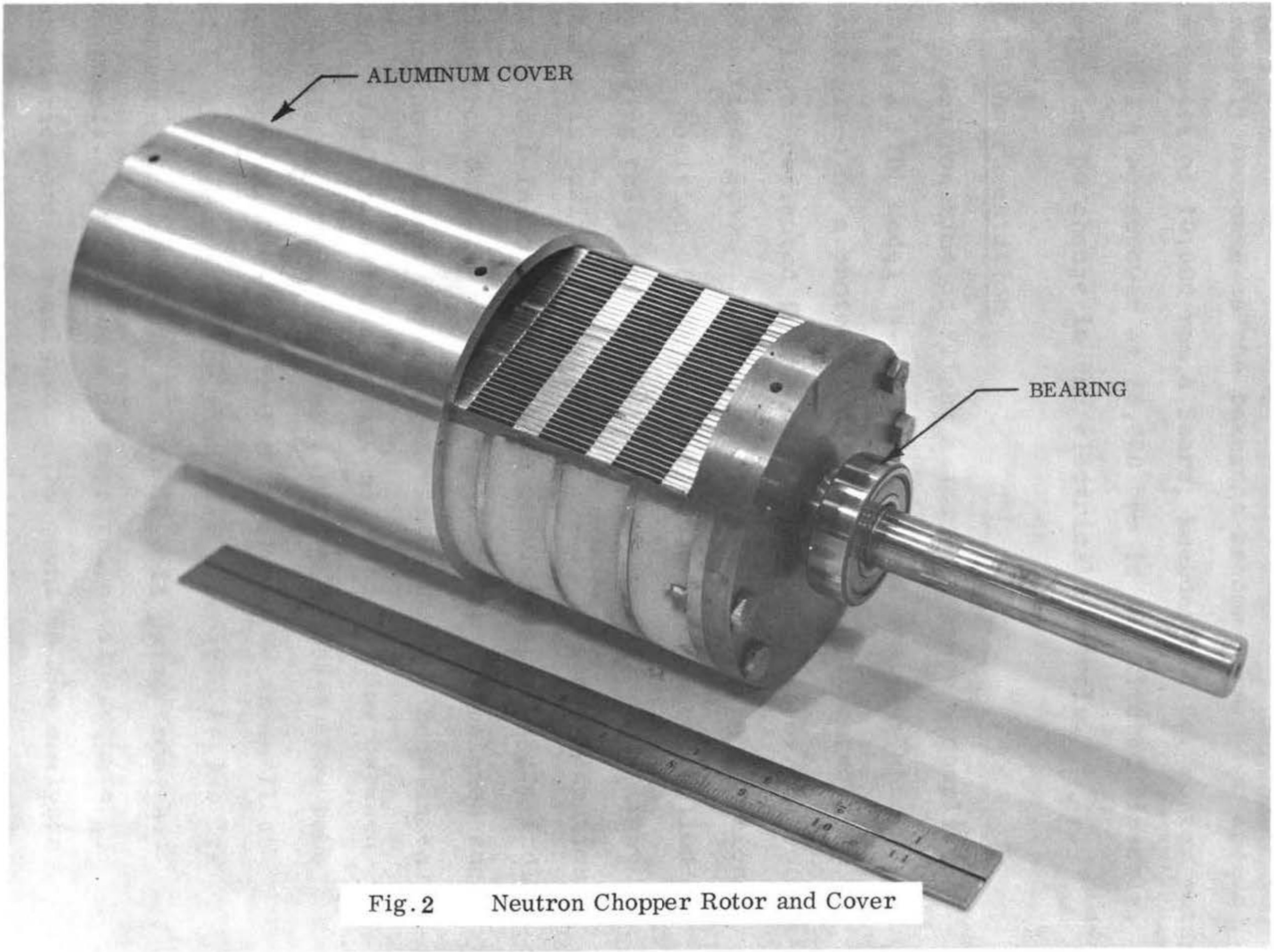


Fig. 2 Neutron Chopper Rotor and Cover

speed of 10,000 rpm is realized. This top speed will probably increase as the bearings become worn. For speeds in excess of 10,000 rpm a Sears, Roebuck and Co. router motor rated 3/4 horsepower at 23,000 rpm is substituted directly, requiring no change in the electrical controls.

B. Instrumentation

Neutron time of flight measurements are accomplished using a RIDL model 34-12B multichannel analyzer which is controlled by a photocell actuated by a collimated beam of light reflected from a mirror on the shaft of the rotor. (See Figs. 3,4). This angle of reflection is a function of the position of the chopper blades and is controlled by moving the position of the light source. This light source is positioned by a gear box achieving a reduction of 80 to 1 in combination with provisions for angle indication from 0 to 16 degrees. The gear box is designed such that the smallest division on the adjustment knob is equivalent to 0.5 minutes (See Fig. 4). The spacing between channels is accomplished by a RIDL Model 54-6 time base generator which can control channel widths as small as 12.5 microseconds. The time base generator begins its sequence upon receiving a 5 to 10 volt pulse from the photocell. This process is repeated until adequate statistics are accumulated. The count in the analyzer memory therefore represents an inverse energy plot with

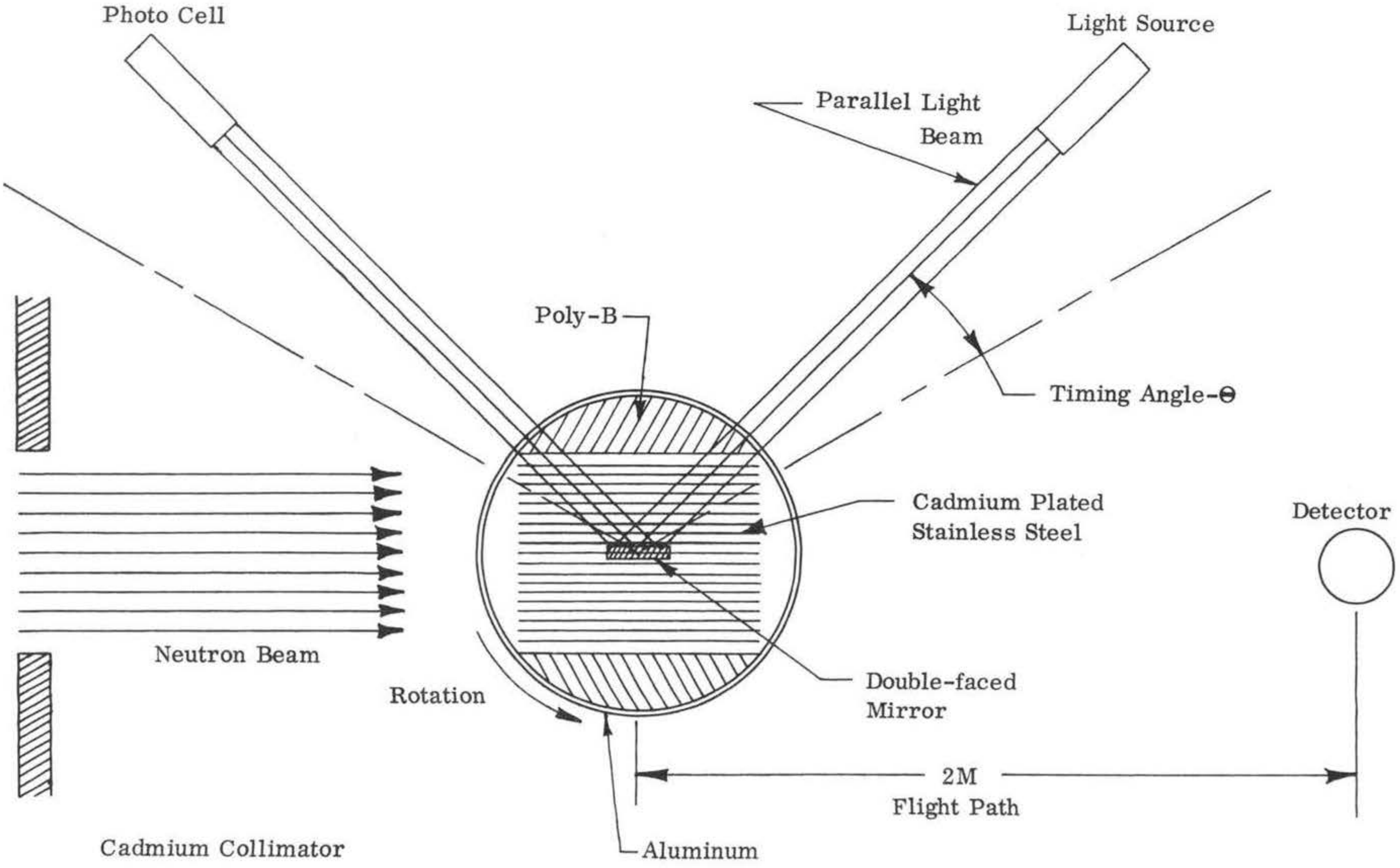


Fig. 3 Rotary Shutter In Open Position

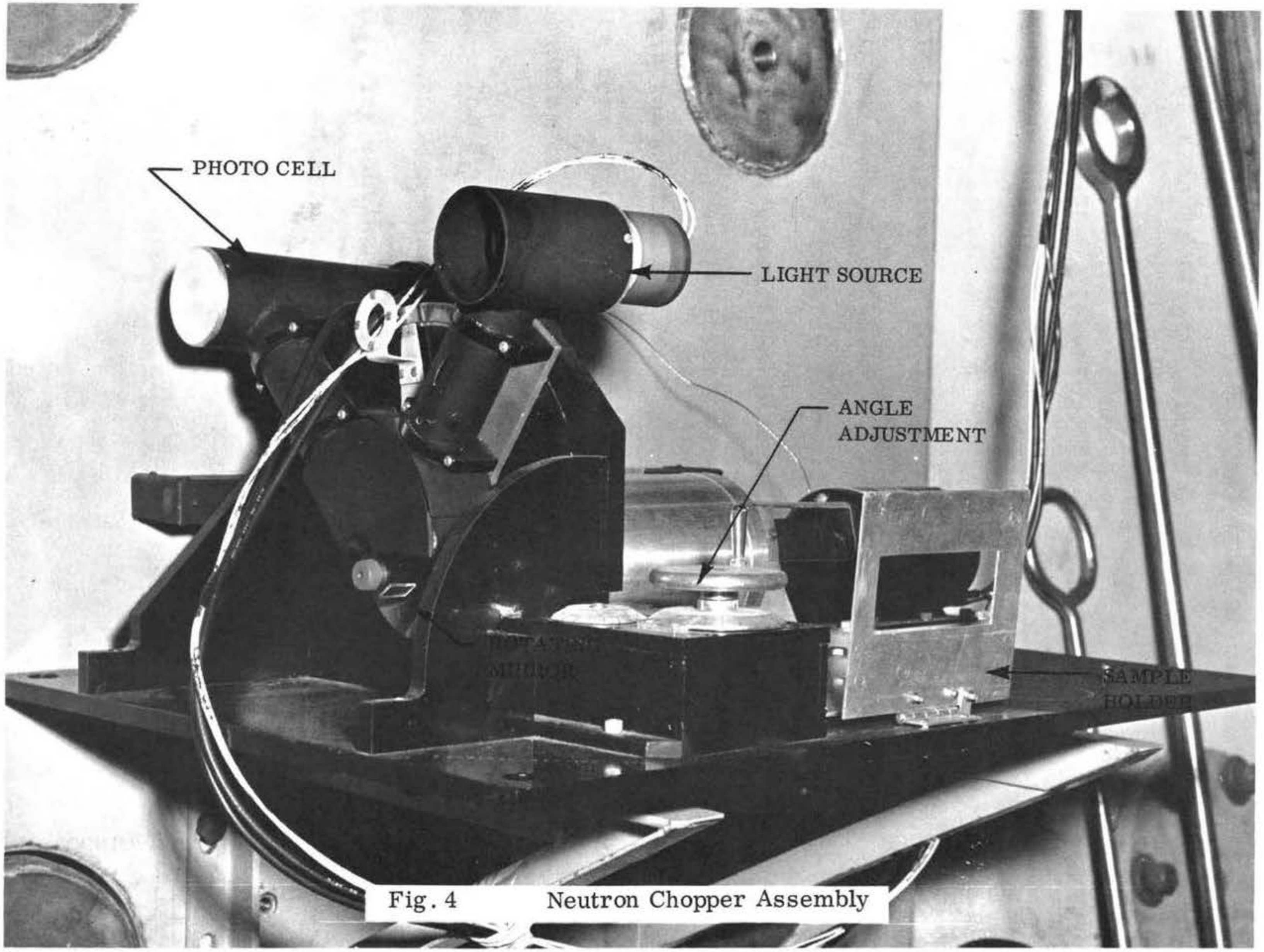


Fig. 4 Neutron Chopper Assembly

the highest energy neutrons appearing in the first channel. A Reuter-Stokes BF_3 proportional counter is used as the neutron time of flight detector. The output of the tube is connected to a pre-amplifier similar to the Minneapolis-Honeywell 1906-H1 (See Fig. 5) whose output is connected to a multichannel analyzer some forty feet away. High voltage is provided by a Tracerlab SC-86 power supply capable of voltages up to 2,500 volts (See Fig. 5). A neutron catcher made of paraffin and boron is located immediately behind the BF_3 counter in order to absorb the remaining neutrons. A model 515A Textronix oscilloscope is used as a general service instrument and particularly to insure that the control pulses have the proper rise time and are free of oscillations and transients that would produce counting or control errors.

C. The Speed Control System

The most desirable chopper would involve a system allowing continuously variable speed which is precisely regulated at any setting. Egelstaff (26) describes a system in which a precision audio oscillator operates a synchronous motor. Since the construction of such a system is economically prohibitive for such a project, a compromise system is designed. A simple synchronous motor would provide constant operation at 3,600 rpm. This speed could then be varied by changing gear ratios. The North Carolina State University chopper (27) is designed on this principle.

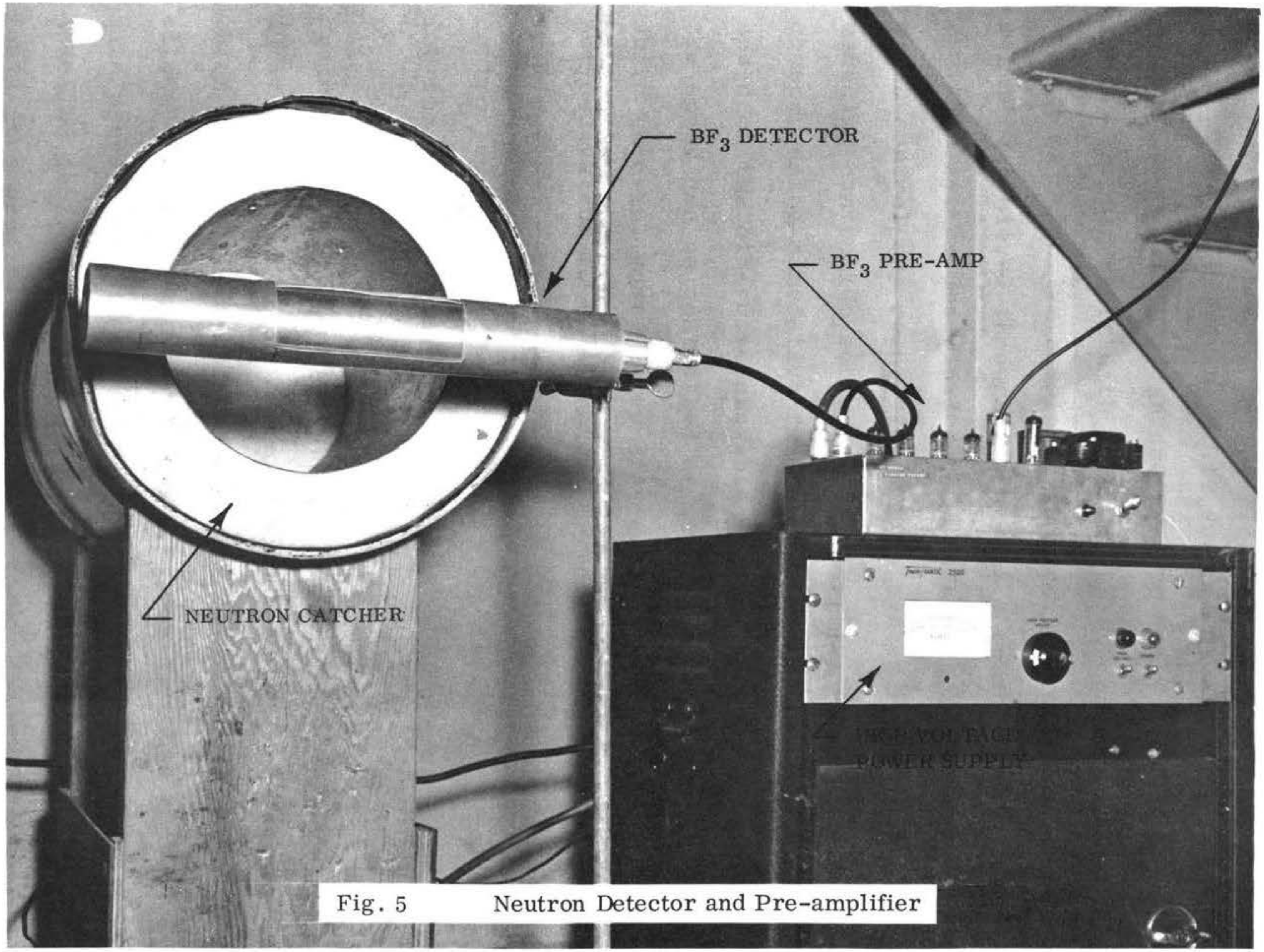


Fig. 5 Neutron Detector and Pre-amplifier

This system permits constant speed operation but the speed must be varied in discrete steps. Also, the thought of belts or gears operating at 15,000 rpm is discouraging. Another possibility is an ordinary DC motor coupled directly to the chopper shaft with a manual speed control. This system is selective but lacks the desired stability that might be achieved through the use of a synchronous system.

The system described herein is a compromise between speed control and regulation: This system employs a manually controlled series motor directly coupled to the chopper using a negative feedback loop to regulate the speed of the otherwise unstable motor. Using this system, the speed can be controlled as with an ordinary DC motor while enjoying some degree of regulation approaching but not equivalent to an AC motor.

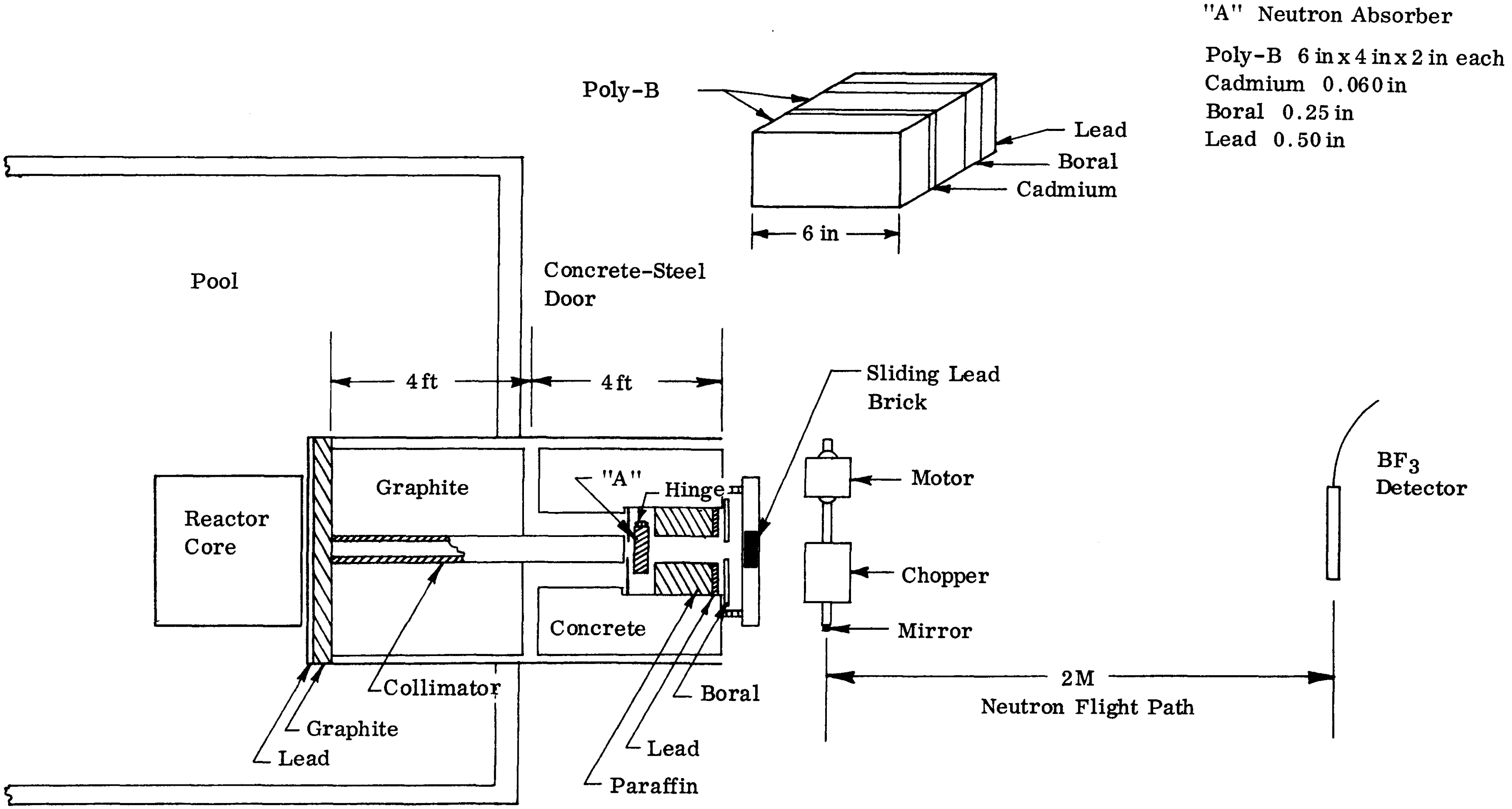
Control of the motor speed is accomplished by a silicon controlled rectifier which obtains its feedback signal during the preconduction time. The feedback is determined by the back emf of the motor during the non-conduction cycle of the diode. (See schematic diagram in Appendix II). Rotational speed is indicated by a multi-vibrator tachometer which is operated from the photocell. This measurement allows the operator to bring the chopper up to an approximate speed which is indicated directly on the tachometer. A scaler deriving its signal from the photocell is provided for a more precise speed determination. The operator may thus use the scaler to calibrate the tachometer at any particular speed.

For ordinary work (i.e., spectrum measurement), the speed regulation inherent in the feedback circuit of the control mechanism is sufficient. However, for more precise work, the input power to the control mechanism should be regulated.

D. The Physical Set Up

The entire chopper assembly is mounted on the thermal column door directly in front of the thermal column. A neutron collimator made of wood approximately seven feet long (Fig. 6) is designed to replace one of the graphite stringers in the thermal column and extend approximately three feet inside the thermal column door. This collimator defines a neutron beam 1-1/2 by 3 inches. A baffle made of cadmium located about two feet inside the thermal column door and attached to the end of the collimator is provided to absorb any remaining neutrons. The neutron beam is again confined immediately after leaving the door and before entering the chopper. Neutron and gamma shutters are provided to control the beam.

After leaving the rotor, the neutrons travel over a flight path of 2.00 m where they are detected by a BF_3 counter. (Figs. 6,7).



Top View Cross Section

Fig. 6 Reactor Thermal Column and Collimators

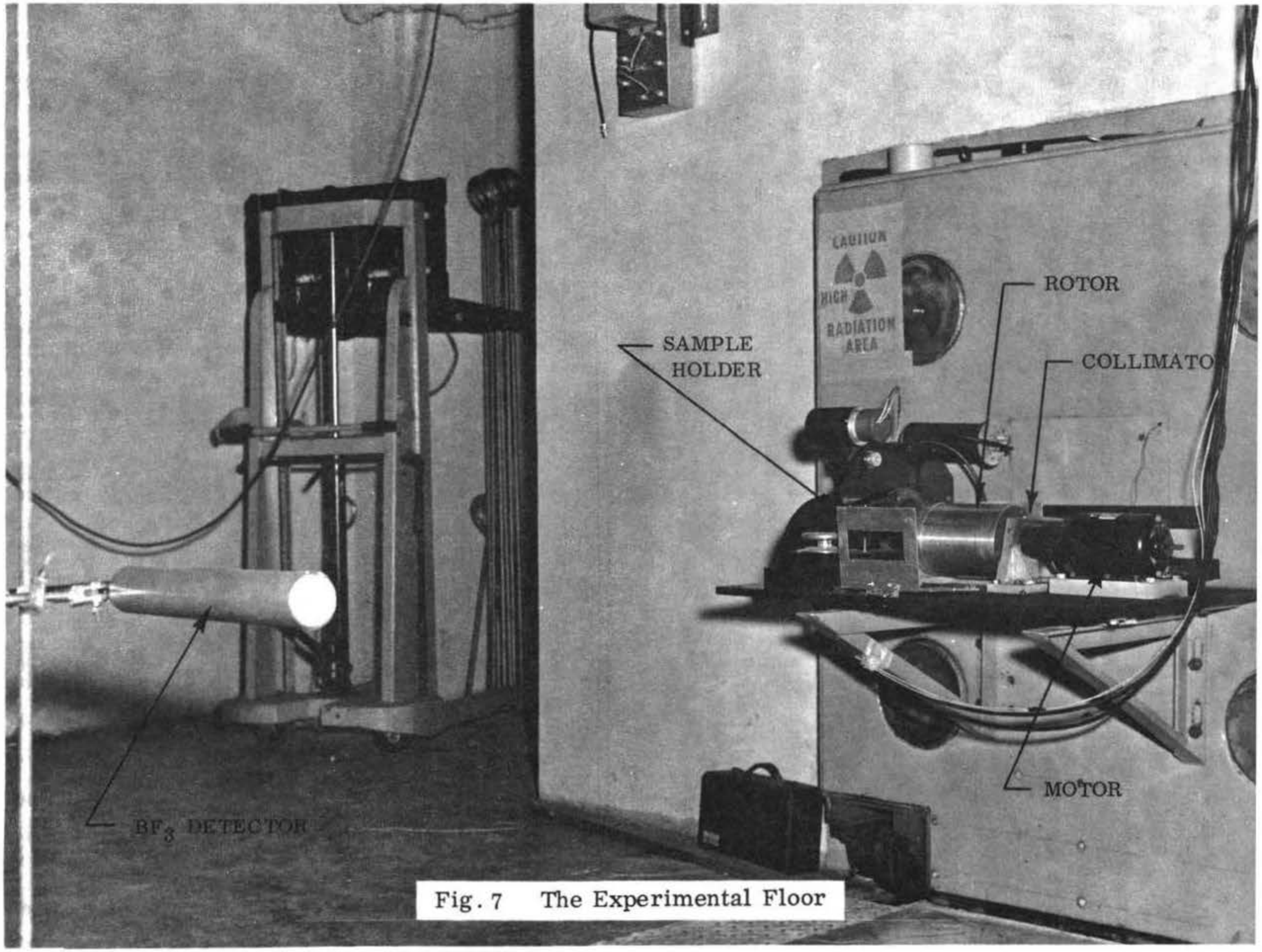


Fig. 7 The Experimental Floor

E. Type of Measurements Available

Valente, Hoag, and others (29, 23,26) describe several experiments which are performed by a pulse neutron source. Several of these experiments are possible using the UMR facility: Neutron flux-energy distributions for a given thickness in the graphite thermal column can be determined. From these data, total cross sections can be calculated. Through the use of a four-pi counting system, absorption cross sections can be measured. Several other experiments may be possible with some additional equipment: i.e., measurements which lead to the decay constant (α) as a function of the geometric buckling (B^2). From the resulting curve the diffusion coefficient (D) and the diffusion length (L) may be calculated. Isenhour and Morrison (32) describe a neutron capture gamma ray activation analysis procedure which offers a number of reactions not available to delayed gamma activation analysis. A neutron chopper is the primary instrument used in this type work.

IV. EXPERIMENTAL DETAILS

A. Discussion

A beam of steady state neutrons coming from the reactor is collimated into a 1/2 by 3 inch column and allowed to pass through a rotating shutter operating from 2000 to 10,000 rpms. These then separate bursts of neutrons are allowed to travel over a fixed distance of 2 meters where they are detected by a BF_3 proportional counter. The faster neutrons arrive at the counter ahead of the slower neutrons thus providing the time of flight energy relationship. At the instant the shutter is open a beam of light triggers a photocell which triggers the multichannel analyzer (MCA) to start counting neutrons at a preset time in microseconds per channel. If the rotating speed is accurately known as well as the geometry of the chopper itself and the distance between the chopper and counter is measured, all of the variables are known for calculating energy as a function of channel number.

B. Procedure

The reactor is brought up to power while the chopper and the associated electronic equipment is allowed to warm up. There is also some indication that the reactor should be allowed to operate for at least 15 minutes at constant power before the neutron count is started.

The speed of operation and the channel width are determined by the energy range of the experiment and the desired resolution. A high rotational speed will produce better resolution but at the same time will decrease the time the chopper is open which will result in the attenuation of the low energy neutrons. The time the chopper remains open (burst width) is given by (5)

$$T = \frac{S}{\omega R}$$

Where:

S = Spacing between blades

ω = Rotational speed (rad/sec)

R = Radius of rotation

The minimum velocity that is transmitted is therefore (5)

$$V_m = \frac{\omega R^2}{S}$$

Therefore, the chopper must be operated at a speed great enough to produce adequate resolution but slow enough to permit the transmission of the desired low-energy neutrons.

For the aluminum cross sections, two runs were made in order to check the accuracy of the data: A high-speed run for good resolution at high energies and a low-speed run for the low-energy neutrons. Rotational speeds of 2200 rpm and 6000 rpm were used for the low and high energy ranges respectively.

It was observed that data taken near the minimum velocity point (V_m) tends to produce inconsistent results. This effect is probably due to the small variation in the chopper speed which would thus cause the V_m to shift thus producing errors in the cross section near that point.

When a stable operating speed is reached, the spectrum is measured without any sample or absorber in the beam. This determination gives the number of neutrons existing in the beam as a function of energy (See Fig. 8). This curve contains the thermal neutron spectrum plus the epithermal neutrons which leaked through the cadmium blades of the chopper. Because of this leakage a suitable background representing the leakage through the chopper must be determined. A thin sheet of cadmium is placed in the beam for this purpose while the analyzer is operated in the subtract mode for a time equal to the previous run.

The sample whose cross section is to be measured is placed in the beam behind the last collimator and the spectrum is recorded. Finally, the cadmium and the sample material are placed in the beam to determine the background which is again subtracted. From the two resulting curves, the cross section is calculated. Because the calculations involved are tedious and repetitious, a suitable computer program is designed for this purpose. The hand calculations indicated in the next section demonstrate the procedure for calculating the cross section for one point on the graph (See Fig. 11). This calculation is repeated for as many

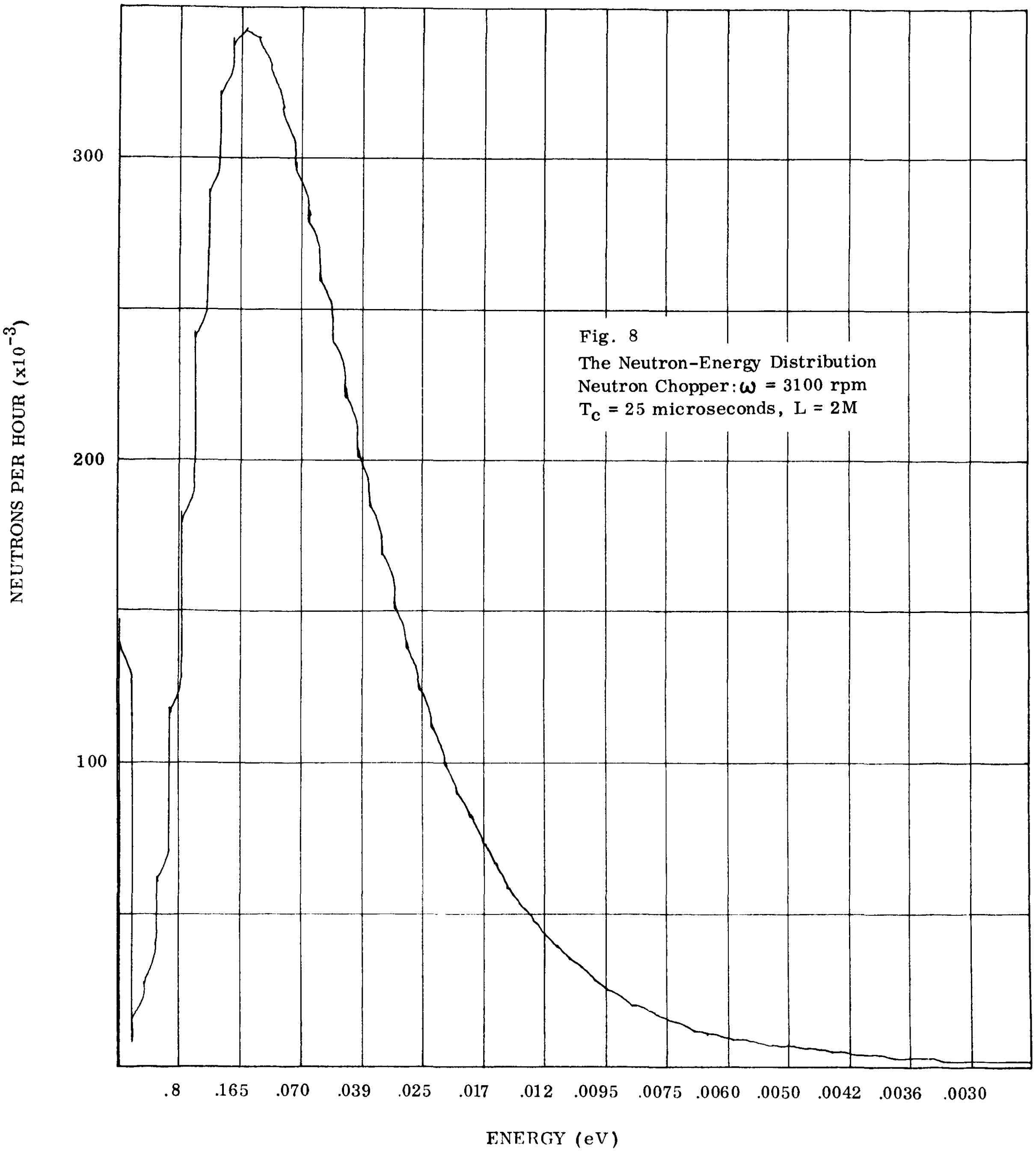


Fig. 8
The Neutron-Energy Distribution
Neutron Chopper: ω = 3100 rpm
T_c = 25 microseconds, L = 2M

Fig. 9 Neutron Chopper Control Panel

points as desired. The computer program is written to handle 99 points. Actually, the chopper is incapable of producing this much data at a particular single speed; however, it is more convenient to process the data taken from the multichannel analyzer if 99 channels are used. The channels which contain poor statistics are then discarded.

C. The UMR Reactor

The UMR Reactor is a light water moderated and cooled pool type reactor which is licensed to operate at a power level of 10 kw. The reactor core contains 14 fuel elements and 4 control elements which contain approximately 2788 grams of 90% U-235 enriched uranium oxide. The core is suspended from a bridge which is moveable on tracks from one end to the center of the pool. For this work, the core is moved to the extreme east end of the pool until it rests against the graphite thermal column which protrudes into the pool. This produces the highest possible neutron flux in the thermal column. A single 4" x 4" x 5' graphite stringer is removed from the thermal column and replaced by the collimator. This leaves about one foot of graphite between the core and the collimator. Because this distance is not adequate to produce a high thermal to fast flux ratio, approximately one foot of moderator is added to the collimator. Hughes (4) suggests that there is an optimum moderator thickness which will produce the maximum thermal to fast flux ratio. This problem should be investigated in order to improve the operation of the chopper.

The present available power (10kw) is found to be adequate but inconveniently low. Better results could be obtained in less time if the now pending application to increase the power level to 200 kw is approved.

V. DATA AND RESULTS

A. Measured Aluminum and Cobalt Cross Sections

These data and results include the measured microscopic cross section of aluminum and cobalt. The aluminum cross section was used as a standard to check the operation of the chopper and to provide a calibration point for the pulse system. The cross sections given in the Second Edition of BNL325 (31) are taken as the standard.

The results shown in Figure 10 include 4 points that are inconsistent with the results obtained on the ANL fast chopper. Several checks were made to check the reliability of these points:

(1) The time base per channel and the rotational speed was changed in order to eliminate the possibility of channel error.

(2) The data was taken several times to disprove the possibility of random error.

(3) The MCA was triggered by an external oscillator with the chopper in the open position as a check on the channel linearity.

Negative results were obtained in all cases. It is believed therefore that these points do exist for the sample measured. It is interesting to note that there is a gap in the ANL data near the points in question.

Very little data is available concerning cobalt slow cross sections. Considerable work (31) has been done in the energy range from .03 eV to 10 MeV but no data was found in the region below .03 eV. This low energy region is of significant importance in thermal reactons because the most probable thermal neutron at 20° C is 0.025 eV.

This paper presents measured thermal cross sections in the range from 0.005 eV to 0.1 eV. The measured cross sections at higher energies which overlap the previously determined values (31) were found to be in good agreement. The cobalt furnished by Metals for Electronics, Inc. was 99.9% pure containing iron, nickel, and copper as impurities. The errors in the cobalt cross section are smaller than the points on the graph except for the extreme low energy range.

TABLE I

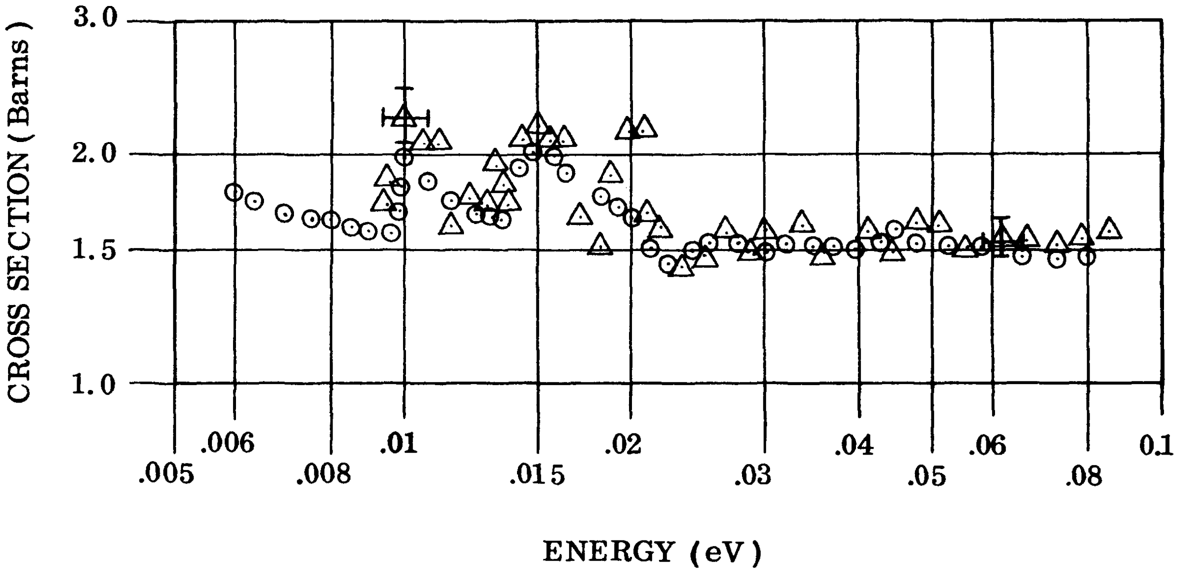
MEASURED ALUMINUM CROSS SECTIONS

Foil thickness: 5/16 in.
Counting time: 1.5 hr.
Chopper Speed: 4,200 rpm
Time base generator: 12.5 μ sec.

Energy (eV)	Cross Section (Barns)	Statistical Error (Barns)
.0878	1.63	0.04
.0794	1.58	0.05
.0722	1.53	0.05
.0659	1.53	0.05
.0604	1.52	0.05
.0556	1.51	0.05
.0513	1.62	0.05
.0475	1.66	0.06
.0441	1.56	0.06
.0411	1.53	0.06
.0383	1.57	0.06
.0358	1.49	0.07
.0336	1.68	0.07
.0316	1.66	0.07
.0297	1.48	0.07
.0280	1.48	0.08
.0264	1.61	0.08
.0250	1.58	0.09
.0237	1.46	0.09
.0225	1.64	0.09

Table I (Cont'd)

.0213	1.72	0.10
.0203	2.22	0.10
.0193	2.22	0.11
.0184	1.78	0.11
.0176	1.53	0.12
.0168	1.69	0.12
.0161	2.12	0.13
.0154	2.03	0.14
.0147	2.26	0.14
.0141	2.14	0.15
.0136	1.77	0.16
.0130	1.90	0.16
.0125	2.02	0.17
.0121	1.73	0.18
.0116	1.89	0.19
.0112	1.78	0.20
.0108	2.17	0.21
.0104	2.10	0.22
.0100	2.30	0.23
.0097	1.89	0.24
.0094	1.81	0.25



⊙—Results From ANL Fast Chopper
△—Results From MSM Slow Chopper

Fig. 10 Slow Neutron Cross Sections of Aluminum

TABLE II

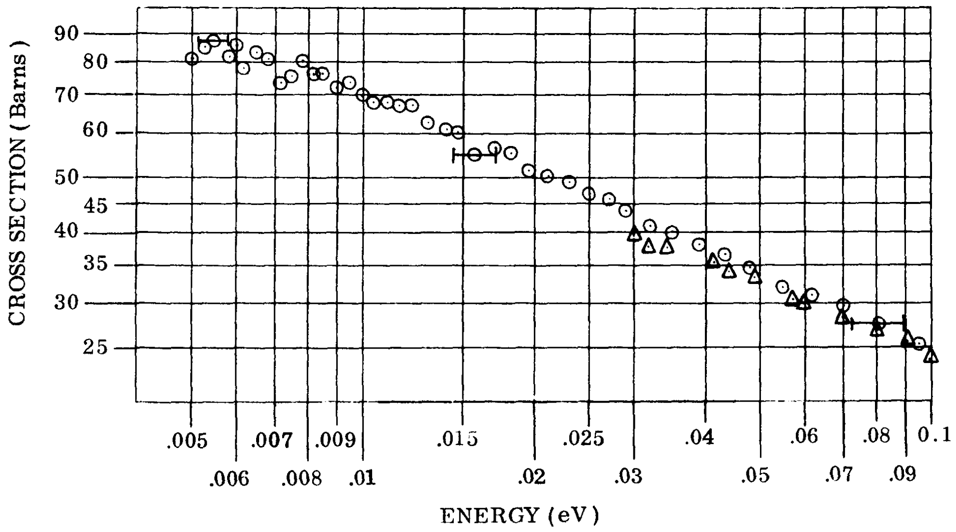
MEASURED COBALT CROSS SECTIONS

Foil thickness:	0.030 in
Counting time:	1.0 hour
Chopper speed:	3100 rpm
Time base generator:	25.0 μ sec.

Energy (eV)	Cross Section (Barns)	Statistical Error (Barns)
.0950	25.9	0.3
.0814	27.4	0.4
.0706	29.7	0.4
.0617	31.1	0.4
.0545	32.2	0.4
.0484	34.8	0.4
.0433	36.9	0.4
.0390	38.0	0.5
.0353	40.5	0.5
.0320	41.5	0.5
.0293	44.5	0.6
.0268	46.5	0.6
.0247	47.6	0.6
.0228	49.5	0.7
.0211	49.8	0.7
.0196	51.9	0.7
.0182	55.4	0.8
.0170	56.0	0.8
.0159	55.5	0.9

Table II (Cont'd)

.0149	59.6	1.0
.0140	61.3	1.0
.0132	62.6	1.1
.0124	68.6	1.1
.0117	67.8	1.2
.0111	68.8	1.3
.0105	68.9	1.4
.0100	70.3	1.4
.0095	74.3	1.5
.0090	72.4	1.6
.0086	77.9	1.7
.0082	76.9	1.8
.0078	80.7	1.9
.0074	75.6	2.0
.0071	73.5	2.1
.0068	81.1	2.3
.0065	82.9	2.4
.0063	78.6	2.5
.0060	86.9	2.6
.0058	82.6	2.7
.0055	88.2	2.9
.0053	86.9	2.9
.0051	80.3	3.0



△ —Results From ORNL Crystal Spectrometer
⊙ —Results From MSM Slow Chopper

Fig. 11 Slow Neutron Cross Section of Cobalt

B. Sample Calculations

The microscopic cross section at a particular energy is given by,

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

Where:

I_o = Beam intensity without absorber

I = Beam intensity with absorber

x = Thickness of absorber

σ = microscopic cross section (barns)

N = Atomic density ($X10^{-24}$)

Example: at 0.032 eV, the cobalt cross section is,

$$\sigma(.032) = \frac{-\ln 8444/115099}{(.0762)(.091)} = 45 \text{ barns}$$

See pages 38 and 39 for data.

The energy in eV is given by,

$$E = \frac{V^2}{1.92 \times 10^{-4}} = \left[\frac{L}{t+T_c/2+T_c(Z-1)+D(Z-1)} \right]^2 \Big/ 1.92 \times 10^{-4}$$

Where:

V = neutron velocity

L = neutron path length

t = time to open first channel

D = dead time per channel

Z = channel number

Example: for a neutron in channel 30,

$$E = \left[\frac{2.0}{5.7+25/2+25(30-1)+12.5(30-1)} \right]^2 \Big/ 1.92 \times 10^{-4} = 0.017 \text{ eV}$$

The resolution in time is given by,

$$t_r = \frac{S}{\omega R}$$

Where:

S = spacing between chopper blades

ω = speed in rad/sec

R = rotational radius

t_r = time chopper remains open

Example: at 4800 rpm,

$$t_r = \frac{1/16}{502 \times 2.5} = 49.8 \ \mu \ \text{sec}$$

or approximately two channels at 25 μ secs per channel. For channel 30, this resolution would produce a maximum error of 0.003 eV.

The analyzer characteristics are not included in this resolution determination. Actually a short analyzer channel width tends to improve the resolution (5) so that the above figure represents a maximum possible resolution error.

The statistical error in barns is given by,

$$\Delta I_o = \frac{\sqrt{A}}{T1}$$

$$\Delta I = \frac{\sqrt{C}}{T2}$$

$$Err = \sqrt{\left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta I_o}{I_o}\right)^2}$$

$$\Delta\sigma = \frac{Err}{x \ N}$$

Where:

ΔI_o = error in the beam intensity

ΔI = error in the beam intensity with absorber

A = total counts in the open beam in time T1

C = total counts in the absorbed beam in time T2

Err = total error in the attenuation

$\Delta\sigma$ = error in the cross section in barns.

Example: at .032 eV, the error in the cobalt cross section is, (See Table IV and V)

$$\Delta I_o = \frac{\sqrt{146870}}{60} = 6.39$$

$$\Delta I = \frac{\sqrt{110128}}{60} = 5.53$$

$$\text{Err} = \sqrt{\left(\frac{6.39}{2450}\right)^2 + \left(\frac{5.53}{1835}\right)^2}$$

$$= \sqrt{6.78 \times 10^{-6} + 9.06 \times 10^{-6}} = 3.98 \times 10^{-3}$$

$$\Delta\sigma = \frac{3.98 \times 10^{-3}}{(.0762)(.091)} = 0.574 \text{ barns}$$

VI. CONCLUSIONS AND RECOMMENDATIONS

A neutron chopper provides a means for directly measuring the neutron-energy distribution in a beam of slow neutrons. This spectrum contains sufficient resolution to permit accurate energy dependent cross section measurements within a certain energy range.

At high energies the resolution becomes poor and limits the effectiveness of the results. At low energies the chopper begins to attenuate neutrons near the cutoff velocity and therefore the low energy region is affected. The chopper will obtain useful results over about one and one half energy decades. This useful range can be moved up or down the energy scale by varying the chopper speed.

Another limitation on the chopper is the availability of neutrons at a particular energy. In order to produce good statistics, a large number of neutrons must be available in the beam at that energy.

The motor bearings should be taken down and lubricated after 10^7 revolutions or after about 100 hours of normal use. If the chopper is operated at high speeds for extended periods the brushes in the motor will probably need replacing at this time also.

All screws and bolts should be checked before each experiment. A serious accident could result if the chopper becomes unbalanced at 10,000 rpm because of the loss of a set screw. In order to maintain balance all screws in the chopper and shaft connector must be returned to their exact position if the device is disassembled.

Once the collimators are aligned, the alignment will remain constant only as long as the thermal column door remains undisturbed. If the door is moved, the system is subject to misalignment because of the loose motion in the wheels which support the door. It is recommended that either the loose motion be corrected or that an easy alignment method be developed.

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APPENDIX I

Detailed Operating Procedure

This section is an attempt to provide a set of instructions which will enable the undergraduate to operate the equipment without a complete understanding of all the instrumentation. There is no attempt to be complete in every detail and no claim is made that this procedure is superior to any other. In addition to the operating procedure, the following suggestions are given so that the experimenter need not duplicate the mistakes of the author.

Suggestions. The triggering pulse produced by the photocell and amplified by the pulse amplifiers should occur at the exact instance the chopper is opened if accurate energy determinations are to be made. It is impossible to set this timing pulse by any static method since the photocell output varies with the speed of the chopper. The photocell does not produce its sharpest rise time at maximum intensity in the rotating light beam. The triggering pulse actually occurs about 2 to 5 degrees before the light beam reaches maximum intensity.

The author suggests that the experimenter establish the zero timing by one of two methods. (1) Use a stroboscope which can be externally triggered by the pulse fed to the analyzer and adjust the timing until the chopper is opened as the strobe flashes. (2) Measure the cross section of nickel and use the known peaks in the cross section curve as calibration points.

The following instructions consist of two parts: (1) general instructions for operating the chopper and (2) instructions for cross section measurement.

Operating Procedure

(1) Connect cable leading to the multichannel analyzer (MCA) as shown in the block diagram in Fig. 12.

(2) Check all the bolts and set screws in the chopper shaft connector, rotating mirror, and chopper mounts.

(3) Check the alignment of the chopper with the neutron beam.

(4) Position the BF_3 chamber as accurately as possible 2 meters from the chopper.

(5) With the reactor operating at one kilowatt, rotate the chopper slowly by hand until the largest neutron count rate is observed.

(6) Check the position of the BF_3 counter by moving it until the largest count rate is observed.

(7) Clean the dust from the rotating mirror.

(8) Start the chopper motor (at a low speed setting) and then turn on the tachometer and light source.

(9) Allow the chopper to operate for five minutes before attempting to set the speed.

(10) Turn on the pulse amplifier and oscilloscope and check the output pulse. The pulse must have a 10v peak and a rise time of 1 μ sec.

(11) The tachometer can now be calibrated using the scaler output as a standard. Note that two pulses are received for each revolution.

(12) Set the MCA to operate on 50 or 100 channels and the time base generator to operate at 12.5, 25, or 50 microseconds as desired.

(13) Make the necessary calculations to determine if the total channel scan time can be included in 1/2 revolution of the chopper.

EXAMPLE: 25 μ sec per channel + 12.5 μ sec dead time per channel = 37.5 μ sec per channel.

37.5 μ sec x 100 channels = 3750 μ sec or 3.7 m sec.

Chopper speed: 100 rev sec or 0.01 sec per revolution or 0.005 sec per 1/2 revolution = 5.0 m sec.

Because 3.7 is less than 5 this combination is possible. Note that 50 μ sec per channel would not work under these conditions.

(14) Set the MCA gain to 1/8 and turn the threshold, upper level, and sensitivity controls fully clockwise.

(15) Make the other necessary changes to permit the MCA to operate with external control in the time mode.

(16) Disconnect the input cable from the internal amplifier and read the total instrument noise with the chopper operating. Reduce the sensitivity just enough to reduce the instrument noise to zero.

(17) Reconnect the input cable and measure the chopper and amplifier noise with the preamp ON and the neutron beam OFF. The noise should not be more than 100 counts per minute. If the noise is excessive, reverse the power plug at the isolation transformer on the chopper speed controller and make sure all ground connections are made. See Fig. 12.

(18) With the reactor operating, open the neutron beam and start the MCA.

(19) A Maxwellian distribution should be observed in about 30 seconds. See Fig. 8.

- -

NOTE: About 5 hours warm up time is required for the tachometer. However, the tachometer need not be operated during this time because the warm up is due to the tubes in the scaler below the tachometer circuit. The motor and tachometer circuit need about 30 minutes to stabilize if the scaler has been left on over night.

Operating Instructions for Cross Section Measurement

(1) Check out the chopper as in the preceeding section. Make sure the chopper is operating at constant speed as indicated by a steady tachometer reading.

(2) Make periodic checks using the scaler to measure the speed.

(3) Measure the open beam for thirty minutes to two hours or as is necessary for statistics.

(4) Place the MCA in the subtract mode and subtract the fast background using the 20 mil cadmium shield.

(5) Print out this data.

(6) Check the chopper speed for consistency.

(7) Place a suitable foil in the holder in front of the rotor and again record the neutron distribution in the same section of the MCA memory as used before. Subtract the background as before.

(8) Print out this data.

(9) These data can be introduced in a computer program to calculate the cross section as a function of channel number and energy.

TABLE III

LIST OF APPARATUS

(1) Neutron Chopper including rotor, electric motor, and photo timing mechanism

(2) Chopper speed controller (Figs. 9, 14)

(3) Tachometer (Figs. 9, 15)

(4) BF_3 Proportional counter, Reuter-Stokes RSN-44A-MG

(5) High voltage power supply, Tracerlab 2500

(6) Pre-amplifier for proportional counter (Figs. 5, 16)

(7) Two pulse amplifiers, RIDL 30-19 and 33-12

(8) Oscilloscope, Tektronix 515-A

(9) Scaler, NRD 320-0A2

(10) Multi-channel Analyzer, RIDL 34-12B

(11) X-Y Recorder, F. L. Moseley 2D-2

(12) Time base generator, RIDL 54-6

(13) Isolation Transformer 115V @5a

(14) Neutron collimators and shutter

(15) Hand held neutron monitor, Nuclear-Chicago DN3

(16) Hand held gamma monitor, Technical Associates CP-4A

APPENDIX II

Schematic and Block Diagrams of Neutron Chopper Circuits

The following section includes block diagrams showing cable connections of all the circuits used in this work. Reference should be made to the manufactor's operating instructions in using the commercial equipment. Schematic diagrams are also provided for all circuits which were designed and constructed for this work.

Some of this equipment is not foolproof and if cables are connected to an improper outlet, the circuit could be damaged. This is particularly true of the tachometer circuit.

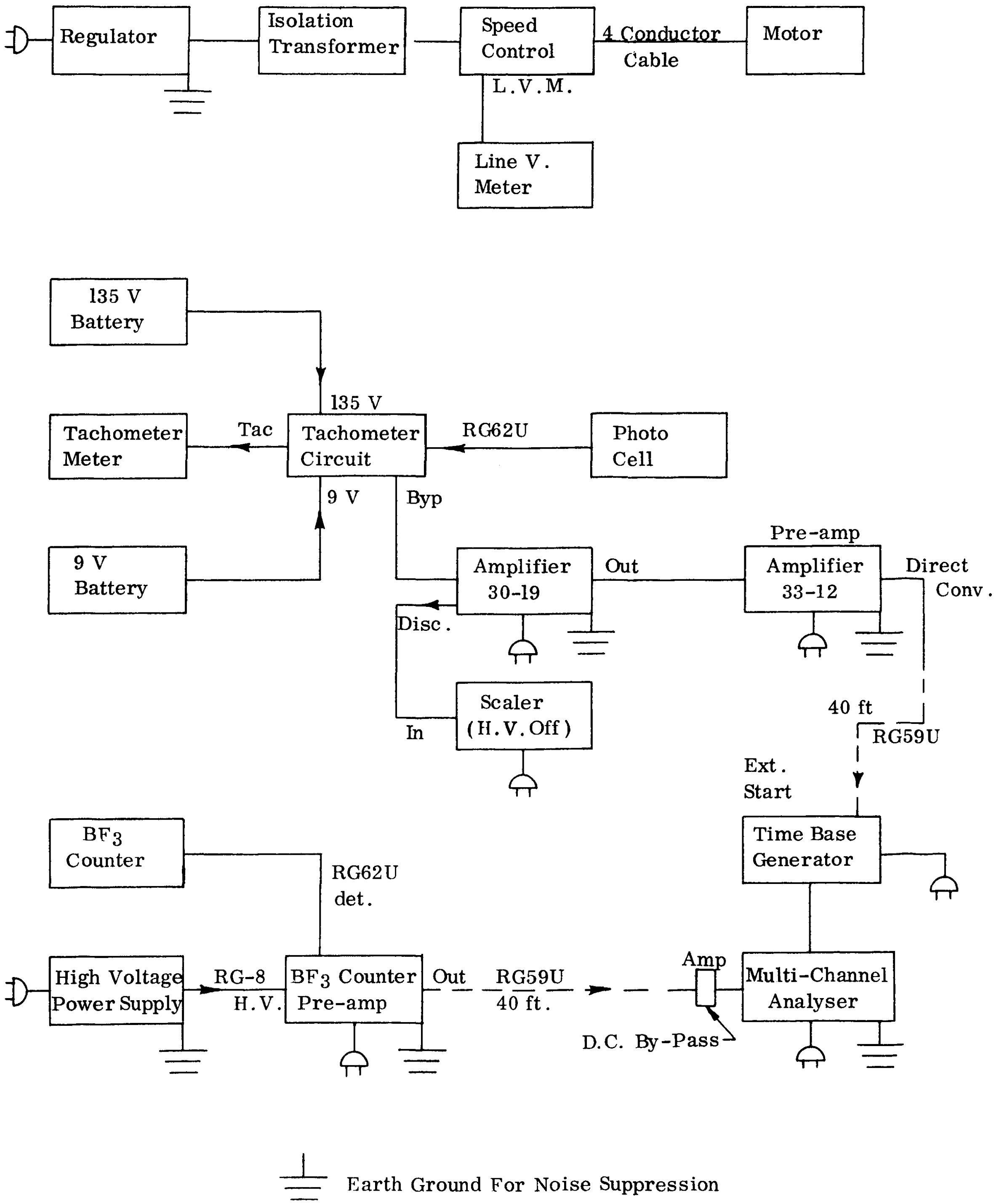
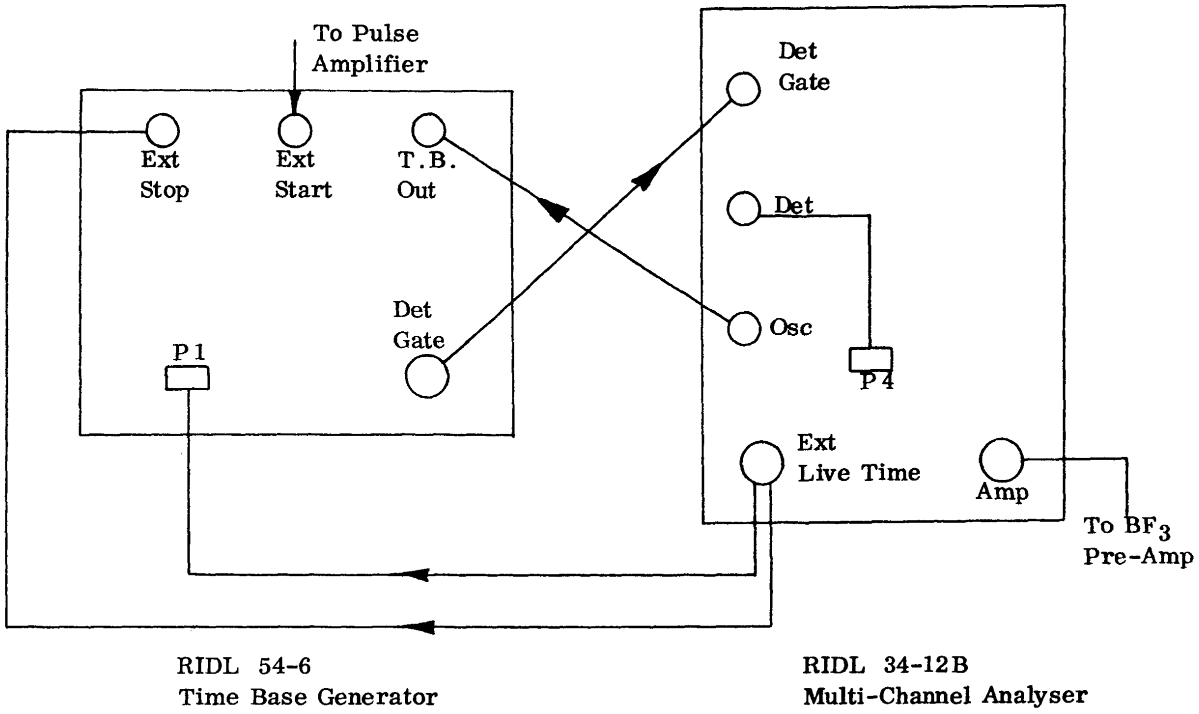
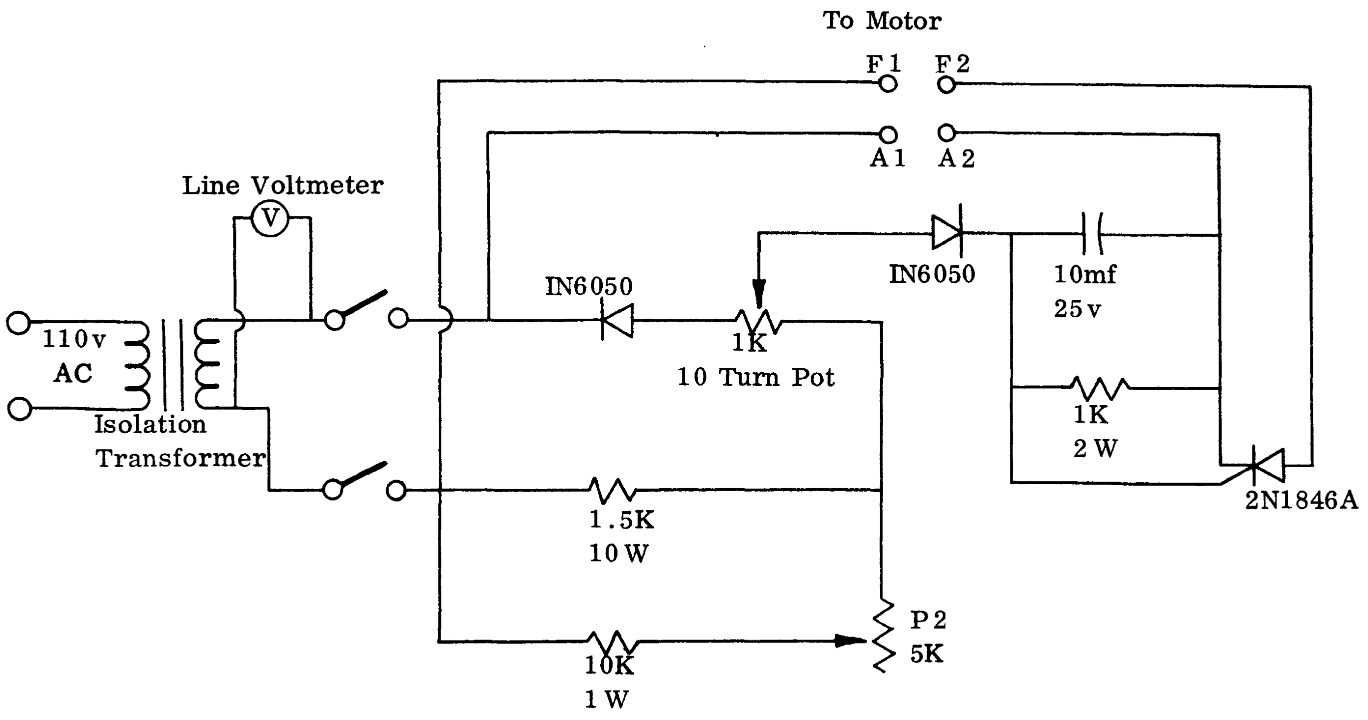


Fig. 12 Wiring Diagram For Complete System



Gain 1/8
Threshold 1000
Upper Level 1100
Time Mode
Sensitivity- as necessary to eliminate Time Base Generator noise

Fig. 13 Connection Diagram for Multi-Channel Analyser



P1- Speed Control
P2- Fine Speed Adjustment
Note: Circuit is isolated from chassis
to reduce noise in other amplifiers

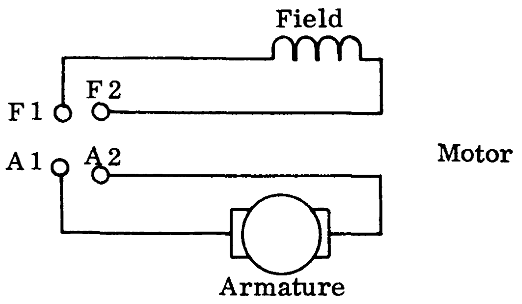
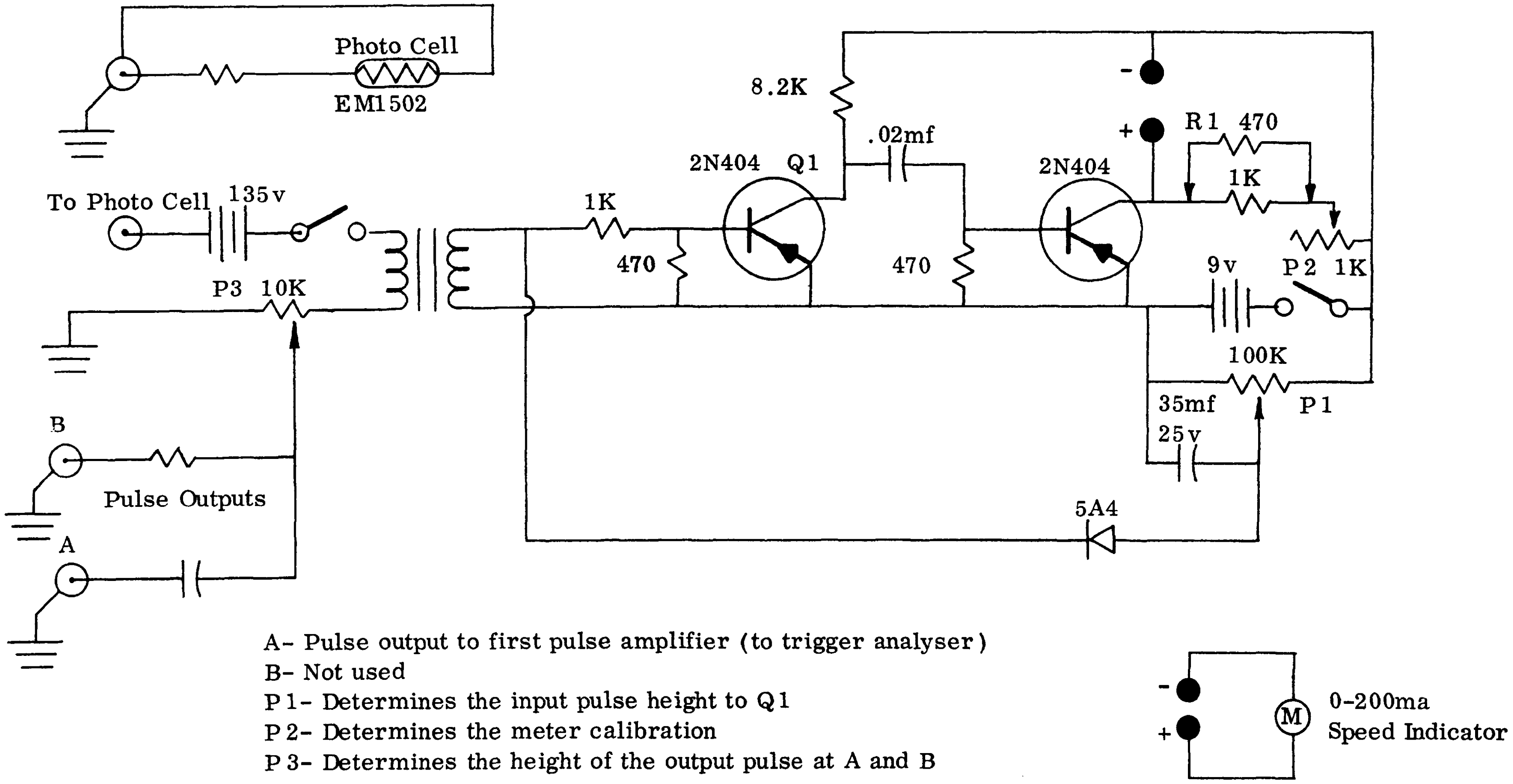


Fig. 14 Schematic Diagram of the Speed Controller



A- Pulse output to first pulse amplifier (to trigger analyser)
B- Not used
P1- Determines the input pulse height to Q1
P2- Determines the meter calibration
P3- Determines the height of the output pulse at A and B

Fig. 15 Schematic Diagram of Tachometer

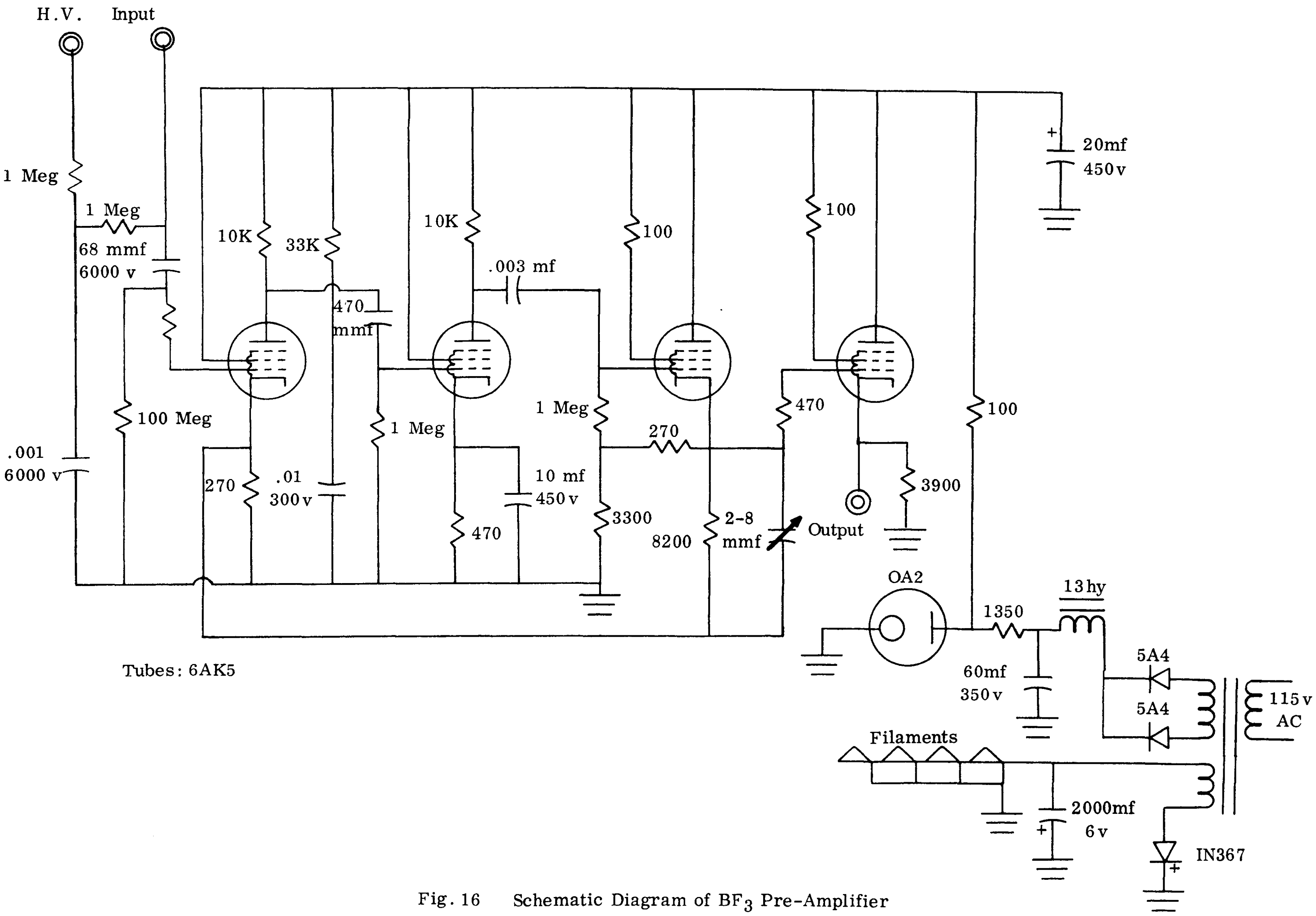


Fig. 16 Schematic Diagram of BF_3 Pre-Amplifier

APPENDIX III

Computer Program and Cross Section Data

This section provides the computer program used to obtain the results in this paper. Included is a sample input data sheet and a sample computer output. These data correspond to the data presented in Section V.

TABLE IV

COMPUTER PROGRAM TO CALCULATE CROSS SECTIONS

```
*LIST PRINTER
C   C***64933NE490E   MOBLEY C M          07/08/66 FORTRAN 2
C      CROSS SECTION BY NEUTRON CHOPPER
       DIMENSION A(100),S(100),C(100),P(100),E(100),DS(100)
       READ 100,W,X,Y,TC
       READ 100,T1,T2
C      W=ATOMS/CC  X=SAMPLE THICKNESS
C      Y=PATH LENGTH TC = TIME PER CNANNEL
       READ 200,(A(I),I=1,99)
C      A= TOTAL NEUTRONS , NO ABSORBER, NO FILTER
C      I= CHANNEL NUMBER
       READ 200,(C(I),I=1,99)
C      C= TOTAL NEUTRONS, WITH ABSORBER, NO FILTER
       DO 50 I=1,99
       F=(A(I)/T1)
       FO=C(I)/T2
C      F= NET COUNTING RATE WITH SAMPLE
C      FO= NET COUNTING RATE W/O SAMPLE
       Z=I-1
       E(I)=(Y/(5.7+TC/2.+(TC*Z)+(12.5*Z)))**2/1.92E-04
C      E= ENERGY AS FUNCTION OF CHANNEL NUMBER
       S(I)=LOGF(F/FO)/(W*X)
C      S= MICROSCOPIC CROSS SECTION
       DF=SQRTF(A(I))/T1
       DFO=SQRTF(C(I))/T2
       ERR=SQRTF((DF/F)*(DF/F)+(DFO/FO)*(DFO/FO))
       DS(I)=ERR/(W*X)
    50 P(I)=F/FO
       PRINT 300
       PRINT 400,(I,P(I),E(I),S(I),DS(I),I=1,99)
       CALL EXIT
   100 FORMAT(10X,5F10.5)
   200 FORMAT(6X,9F7.0)
   300 FORMAT (12H CHAN NUMBER,4X,11HATTENUATION,5X7H ENERGY,8X
      2,5HBARNS,7X,5HERROR //)
   400 FORMAT(8X,I4,4F14.7)
       END
```

TABLE V

INPUT DATA* FOR COBALT CROSS SECTION

Nuclei per Unit Vol. x 10^{-24}	Thickness (cm)	Flight Distance (m)	Channel Width (μ sec)
.091	.0762	2.0	25.0

Counting Time (min)

Open	Absorber
60.00000	60.00000

Counts Recorded per Channel (Open)

14150.	25412.	57786.	109203.	170602.	227797.	273277.	304322.	322158.
326839.	324086.	314806.	301387.	285191.	268648.	250978.	230771.	213251.
195752.	178847.	163064.	146870.	133119.	120316.	108336.	97711.	88994.
80739.	72929.	65418.	57928.	52073.	47030.	42933.	38882.	34970.
31257.	27690.	24958.	22387.	19914.	18045.	16278.	14847.	13244.
11724.	10646.	9568.	8807.	8293.	7534.	6953.	6594.	6126.
5401.	5060.	4290.	4107.	3996.	3542.	3274.	2978.	2643
2485.	2263.	1971.	1927.	1546.	1567.	1514.	1370.	1224.
1038.	983.	912.	835.	721.	639.	654.	580.	497.
497.	399.	455.	318.	299.	308.	289.	310.	255.
236.	92.	170.	215.	245.	238.	114.	131.	42.

Table V (Cont'd)

Counts Recorded per Channel (Absorber)

11957.	22678.	50504.	95345.	148670.	197759.	236909.	262797.	276129.
279680.	275386.	264516.	251689.	235803.	218547.	202273.	184499.	167448.
151482.	137356.	123058.	110128.	97725.	87133.	77879.	69280.	62998.
56330.	49637.	44341.	39401.	34435.	30729.	27813.	24156.	21840.
19392.	17162.	15326.	13373.	12047.	10509.	9545.	8484.	7840.
7039.	6063.	5383.	5103.	4539.	4248.	3770.	3608.	3509.
2805.	2726.	2505.	2313.	2011.	1769.	1683.	1432.	1329.
1264.	1145.	1002.	919.	926.	840.	729.	587.	592.
454.	462.	428.	331.	320.	404.	295.	294.	213.
232.	242.	145.	161.	126.	146.	101.	122.	84.
88.	118.	105.	106.	36.	2.	102.	96.	70.

*each line contains the data on one computer card.

TABLE VI

COMPUTER OUTPUT DATA FOR COBALT CROSS SECTIONS

CHAN NUMBER	ATTENUATION	ENERGY	BARNS	ERROR (σ)
1	1.1834071	62.8949680	24.2850860	1.7914007
2	1.1205573	6.7150359	16.4151810	1.3173743
3	1.1441865	2.3984292	19.4245760	.8784632
4	1.1453458	1.2195722	19.5706200	.6391973
5	1.1475213	.7363880	19.8442810	.5116586
6	1.1518919	.4923684	20.3925060	.4432409
7	1.1535104	.3522342	20.5949940	.4048326
8	1.1580117	.2644075	21.1566550	.3840287
9	1.1666938	.2057587	22.2338450	.3739968
10	1.1686176	.1646610	22.4714470	.3714737
11	1.1768427	.1347509	23.4829060	.3737549
12	1.1901208	.1123075	25.1009210	.3803786
13	1.1974579	.0950376	25.9872640	.3894050
14	1.2094460	.0814653	27.4238410	.4014000
15	1.2292458	.0706056	29.7656260	.4154232
16	1.2407884	.0617810	31.1134630	.4309096
17	1.2507981	.0545130	32.2721900	.4503822
18	1.2735356	.0484560	34.8702040	.4708785
19	1.2922459	.0433552	36.9735090	.4934931
20	1.3020690	.0390193	38.0656060	.5173946
21	1.3250987	.0353028	40.5940030	.5445594
22	1.3336299	.0320931	41.5194930	.5748480
23	1.3621796	.0293020	44.5741480	.6074912
24	1.3808316	.0268597	46.5354210	.6415141
25	1.3910810	.0247106	47.6019060	.6775079
26	1.4103781	.0228094	49.5886790	.7162662
27	1.4126480	.0211195	49.8205920	.7508794
28	1.4333215	.0196107	51.9157890	.7917018
29	1.4692467	.0182580	55.4858260	.8391425
30	1.4753388	.0170405	56.0825540	.8870994
31	1.4702164	.0159409	55.5809750	.9417310
32	1.5122113	.0149444	59.6424980	1.0016717
33	1.5304760	.0140385	61.3738840	1.0578333
34	1.5436306	.0132125	62.6081110	1.1100307
35	1.6096207	.0124573	68.6450570	1.1814572
36	1.6011904	.0117651	67.8877660	1.2437751
37	1.6118502	.0111290	68.8446690	1.3182692
38	1.6134483	.0105432	68.9875810	1.4010353
39	1.6284745	.0100024	70.3244320	1.4799620
40	1.6740447	.0095022	74.3045580	1.5761225
41	1.6530256	.0090385	72.4823770	1.6645431
42	1.7170996	.0086080	77.9666850	1.7696114
43	1.7053954	.0082076	76.9803270	1.8591671
44	1.7500000	.0078344	80.7037260	1.9626848

Table VI (Cont'd)

45	1.6892857	.0074862	75.6115730	2.0550030
46	1.6655774	.0071606	73.5732810	2.1745096
47	1.7558964	.0068558	81.1888160	2.3202875
48	1.7774475	.0065701	82.9480450	2.4570610
49	1.7258475	.0063019	78.6995220	2.5371163
50	1.8270544	.0060498	86.9177480	2.6626548
51	1.7735404	.0058125	82.6306950	2.7669927
52	1.8442970	.0055889	88.2723550	2.9167885
53	1.8276052	.0053779	86.9612160	2.9863348
54	1.7457964	.0051787	80.3569030	3.0531581
55	1.9254901	.0049904	94.4853810	3.3563390
56	1.8561995	.0048121	89.2000670	3.4262780
57	1.7125748	.0046432	77.5861620	3.6263172
58	1.7756160	.0044831	82.7993710	3.7490473
59	1.9870711	.0043311	99.0253720	3.9428807
60	2.0022611	.0041867	100.1236000	4.1985908
61	1.9453356	.0040494	95.9641340	4.3254536
62	2.0796089	.0039188	105.5896600	4.6375545
63	1.9887133	.0037943	99.1445060	4.8495021
64	1.9659810	.0036757	97.4865660	4.9822394
65	1.9764192	.0035626	98.2502260	5.2300806
66	1.9670659	.0034546	97.5661270	5.5953065
67	2.0968444	.0033515	106.7799500	5.7812592
68	1.6695464	.0032529	73.9165250	5.9926321
69	1.8654762	.0031586	89.9190020	6.1669086
70	2.0768175	.0030683	105.3959600	6.5011705
71	2.3339012	.0029819	122.2262400	7.1140954
72	2.0675676	.0028990	104.7522100	7.2195476
73	2.2863437	.0028196	119.2572800	8.1144941
74	2.1277057	.0027434	108.8870000	8.1346675
75	2.1308410	.0026702	109.0993500	8.4496106
76	2.5226585	.0025999	133.4419600	9.3668949
77	2.2531249	.0025324	117.1466100	9.6869341
78	1.5816831	.0024675	66.1200320	9.1665234
79	2.2169491	.0024050	114.8123700	10.1143230
80	1.9727889	.0023448	97.9850910	10.3245630
81	2.3333332	.0022869	122.1911300	11.8104050
82	2.1422413	.0022311	109.8688500	11.4668780
83	1.6487603	.0021774	72.1097840	11.7500170
84	3.1379310	.0021255	164.9164400	13.7527490
85	1.9751553	.0020755	98.1579740	13.9490570
86	2.3730158	.0020272	124.6231100	15.3171220
87	2.1095890	.0019806	107.6538200	14.4903780
88	2.8613861	.0019356	151.6117300	16.6696410
89	2.5409835	.0018921	134.4857600	15.4129110
90	3.0357143	.0018500	160.1405600	18.1423560
91	2.6818182	.0018094	142.2651400	18.0126960

APPENDIX IV

Hazard Analysis for Use of the Neutron Chopper

Neutrons. The nature of this experiment requires that a beam of neutrons be brought out of the thermal column into the experimental area. This is accomplished by removing one of the graphite stringers and allowing a collimated partially moderated beam of neutrons 1 1/2 by 3 inches to enter the room. The flux in this beam is approximately 10^7 neutrons per square centimeter per second.

This beam emerges from the thermal column and passes through the rotating chopper which is constructed of stainless steel which has been cadmium plated, aluminum, and ordinary steel. The initial collimation is accomplished by a 1 1/2 x 3 in. hole cut into cadmium which is located about two feet within the thermal column door. Additional collimation is accomplished by a sheet of boral which is bolted to the door and another cadmium baffle located about one inch from the chopper. After passing through the baffles, neutron chopper, and detector tube, the remainder of the beam travels to the beam catcher which is made of .15 lb. boric acid per lb. of paraffin. The neutron beam should be completely absorbed in the catcher.

The neutron beam will cause activation of the air through which it passes. It has been estimated* that the activity of the room air would be approximately 10^{-7} mc/ml.

*Presented to the Reactor Safety Committee, May, 1966.

which is less than the permissible concentration permitted by AEC regulations. Almost all the neutron scattering around the chopper components occurs throughout a small angle in the vertical direction. Negligible neutron scattering exists to the sides of the chopper. However, as a safety precaution against scattered neutrons and gamma activity the control panel is located some 15 feet away from the chopper.

Gamma rays. The gamma intensity in the neutron beam is approximately 650 mr/hr and some neutron-gamma activation exists in the chopper components and in the neutron catcher. This gamma activity (outside of the beam) is less than 1 mr at 3 feet.

Radiation measurement. A monitor for gamma radiation is mounted on the east wall of the experimental room. This gives an annuciation and a rundown when the level exceeds ten mr per hour. A neutron monitor is also installed in the experimental room and is monitored in the reactor control room.

Neutron and gamma hand survey equipment is provided in the experimental room for the purpose of personnel safety. The neutron beam is turned on or off by an absorbing shutter made of 4 in. Poly-B, 60 mil cadmium and 1/2 in. lead. This shutter which is located two feet within the thermal column door can be raised or lowered by a cable extending through the door. The gamma beam is controlled by a four inch lead brick which is mounted in front of the beam port. It is proposed that an automatic sliding absorber be installed which is controlled from the control room and connected to the already existing rotating red beacon which would come on automatically when the beam is open.

VITA

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