

THE DESIGN, CONSTRUCTION AND OPERATION
OF A SLOW NEUTRON CHOPPER

by 1264

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NOMENCLATURE

a'	Distance for neutron intersecting Y-axis by t'_0
d	Rotor slit width
d'	Polycrystal interplanes spacing
d'_m	Maximum polycrystal interplanes spacing
D	Rotor diameter
$f(v, t_0)$	Neutron burst for given neutron velocity
$I(E)$	Transmitted neutron beam
$I_0(E)$	Incident neutron beam
$J(v), J(x)$	Slit transmission function
z	Thickness of the window material
L_{max}	Maximum flight path
n	Integer number
$n(t)$	Neutron density per unit time
P	Density of the aluminum
R	Radius of the rotor
R'	System resolution
R_i	Inner diameter of the aluminum shell
R_o	Outside diameter of the aluminum shell
s_t^{max}	Maximum tangential stress
t	Time variable
t_0, t'	Time-of-flight reference
t'_0	Time required for neutron reaching a'
Δt	Time uncertainty
T_n	Time duration of the neutron burst

v	Neutron velocity
v_{cut}	Neutron cut-off velocity
X-Y	Laboratory coordinate system
x-y	Rotating slit coordinate system
x	$R(\omega/dv)^{1/2}$
y_0	The <u>i</u> th slit distance from the center of the rotor
θ	Rotation angle
λ	Neutron wavelength
γ	Poisson's ratio of the aluminum
τ	Channel length
ϕ	Incident beam angle
ψ	Tangential angle
ω	Rotor angular speed

1.0 INTRODUCTION

In 1935, not long after the discovery of the neutron, Dunning⁽¹⁾ and Fink⁽²⁾ were the first to use a mechanical velocity selector (chopper) to demonstrate that neutrons moderated in paraffin had a Maxwell distribution of velocity. E. Fermi et al.,⁽³⁾ in 1947, first used the chopper to measure the thermal neutron cross-section of boron from the thermal column of a nuclear reactor in Argonne National Laboratory. Since that time, more efforts have been made to develop a more complicated chopper in order to be able to measure the cross-section of materials for other than the Maxwell velocity distribution. The next major development, the so called "Fast Neutron Chopper"⁽⁴⁾ was first developed in Brookhaven National Laboratory in 1954. Choppers with different geometrically shaped slits have also been created for improving the flat-plate type chopper (also Fermi type chopper) transmission probability.

The method for measuring the energy of a neutron by determination of its velocity is quite straightforward. To apply the same technique to a group of neutrons extracted from the nuclear reactor beam port requires the provision of a neutron interrupting device. The most common device used is a revolving mechanical shutter, the so called "chopper". For a linear neutron flight path, the time of arrival at the end of the path for each individual neutron depends only on its velocity. The counting pulses generated by neutrons reaching the neutron detector which is positioned at the end of the flight path are separated in time according to the different flight times. These pulses are recorded in a multi-channel time analyzer in which each channel is gated in discrete time intervals. Each channel then represents a very narrow range of neutron flight time corresponding to a certain number of neutrons

of nearly the same velocity. This narrow range of neutron flight time in each channel is equivalent to a neutron energy interval in each channel. The multi-channel time analyzer records the number of counts from neutrons in each of these channels and the neutron velocity (or wave-length) distribution in the neutron beam which is being investigated can be determined. By this means the energy spectrum of the neutron beam is determined from a time-of-flight spectrum.

A Fermi type of slow neutron chopper was designed and fabricated for the Kansas State University Triga Mark II Reactor. The initial chopper operation as well as neutron energy spectrum measurements are described in this work. A description of the chopper mechanical fabrication and chopper transmission probability, which is essential to the understanding and successful interpretation of experimental results, is also presented in this work.

2.0 CONSTRUCTION OF THE NEUTRON CHOPPER

2.1 Design Considerations

2.1.1 Physical Considerations

2.1.1.1 Maximum Neutron Energy Range. The aim of this work is to measure the thermal neutron spectrum from the tangential beam port of the KSU Triga Mark II Reactor by constructing and operating a slow neutron chopper. The energy spectrum to be measured covers the energy range from 0.3 eV to 0.001 eV. There are several available materials that can be used as an absorbing medium in the neutron chopper such as ^{48}Cd , ^{62}Sm , Sm_2O_3 , ^{63}Eu , Eu_2O_3 , and ^{64}Gd . After examining the physical properties, mechanical properties, commercial availability, and costs of these materials, cadmium was chosen as the absorbing medium for the slow neutron chopper.

2.1.1.2 Thickness of Absorbing Medium--Cadmium. Cadmium foil at sufficient thickness can cut off all neutrons with energy below 0.4 eV. Actually the cadmium cut-off energy will vary with the thickness of cadmium chosen. A thickness of 0.03 inch of cadmium is adequate to achieve a reasonably small transmission of neutrons below a cut-off energy 0.4 eV for isotropic neutron flux. For a collimated neutron flux as used in this work, a thickness of twice this amount is necessary⁽⁵⁾. Thus a total thickness of 0.06 inch was used by using twenty-one layers of 0.003 inch cadmium foil.

2.1.1.3 Energy Resolution. The resolution of time-of-flight during measurement of the neutron energy spectrum determines the velocity or wavelength resolution and energy resolution obtainable. The time duration of the neutron burst, T_n , as defined in section 3.4 in this report, plays an important

role for determination of the time resolution. A thickness of 0.03 inch of aluminum foil for the neutron window material of the chopper of diameter 2.8 centimeters gives a neutron burst duration of 18.5 microseconds at 250 rotations per second. This is calculated by⁽⁶⁾

$$T_n = \frac{2\ell}{\omega D}$$

where ω is the angular speed of the rotor (radian/second), T_n is the time duration of the neutron burst (microsecond), ℓ is the thickness of window material (cm), and D is the rotor diameter (cm).

The diameter of the rotor was previously determined by considering the maximum neutron flight path available in the reactor bay.

2.1.2 Mechanical Runture Consideration

A neutron chopper requires a metal shutter to be rotated at high speed. The stress induced in the shutter due to the rotation may reach the failure value for the material. Thus safety was an important factor in the design of the rotating shutter. If only the maximum tangential stress in the rotating aluminum shell which contains the aluminum and cadmium sandwich is considered, then

$$S_t^{\max} = \frac{1}{4} \cdot \frac{P\omega^2}{386.4} \left[(3 + \gamma) R_i^2 + (1 - \gamma) R_o^2 \right] \quad (7)$$

where ω is the angular speed of the shutter, P is the density of the aluminum,

R_i and R_o are the inner diameter and outside diameter of the aluminum shell, respectively, and γ is Poisson's ratio for the material. In this design at the contemplated ω , 15,000 rotations per minute, $S_t^{\max}$ is 900 psi. However, this is not the maximum stress which occurs. Since two stainless steel end caps are fastened to this aluminum shell, three 3/64 inches holes were tapped into each end of the aluminum shell, these holes give rise to stress concentration points. This stress is also a tangential stress in the shell and is three or four times larger than $S_t^{\max}$. In this work, 6061-T6 aluminum is the material used to construct the rotating shell. The yield stress for this material is 58,000 psi⁽⁸⁾ which is larger than the stress occurring at the stress concentration points by approximately a factor of 15.

2.2 Fabrication

First 3 inch by 1½ inch by 0.032 inch aluminum plates and 3 inch by 1½ inch by 0.003 inch cadmium foils were cut. The sandwich assembly was formed and placed between two ¼ inch thickness clamping plates (also aluminum) with four bolts in the four corners for holding these foils together. Precaution was taken to avoid any deformation of the soft cadmium foils during tightening of the four bolts. Then the edges of the sandwich assembly was squared with a shaper, after which it was chucked in a lathe and machined to a cylindrical shape with a diameter of 2.8 cm. It was then pressed into an aluminum sleeve of inner diameter 2.8 cm and about 5 cm length. After the sandwich was pressed fully into the sleeve, both ends of the sandwich were faced off. The whole machined rotor, finally, was supported by two end plates of the aluminum housing

which contains the rotor during rotation. The aluminum housing not only contains the rotor but also is capable of containing the fragments of the rotor if it ruptures. Two $\frac{1}{4}$ inch by $\frac{1}{2}$ inch slots were cut in either side of the housing in order to permit the neutron beam to directly impinge on the rotor without suffering neutron intensity attenuation. The component parts of the complete chopper assembly are shown in APPENDIX A.

3.0 THEORY OF THE NEUTRON CHOPPER

3.1 Neutron Motion Trajectory

The theory concerning slow neutron choppers is essential to be able to understand and to interpret the experimental results. An excellent and detailed derivation of neutron chopper theory was written by R. S. Stone⁽⁹⁾ in 1956. Other authors such as V. F. Turchin⁽¹⁰⁾ in U.S.S.R. and C. Van Kijk⁽¹¹⁾ in Norway also presented their expressions of the neutron transmission function. A comprehensive review of the neutron chopper theory which pertains to the neutron chopper operation is given in the following paragraphs.

In order to determine the shape of the neutron burst formation of the chopper, the mathematical expression of passage of neutrons through the chopper slit is first derived. Let X, Y , and x, y , be designated as the coordinates of the laboratory system and rotating slit system respectively. The z -axes of both systems are taken to lie along the rotor shaft. The neutron beam coming out from the collimator lies along the X -axis, when $t=0$, i.e., counting starts, the x -axis and X -axis coincide. After a small amount of time has elapsed, the rotation angle $\theta = \omega t$ is obtained where ω is the rotor angular velocity and serves as a parameter. The relation between the X - Y coordinate and the x - y coordinate is thus expressed by the rotation transformation matrix (see Fig. 1),

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix}$$

Now, suppose that a neutron with velocity v reaches the Y -axis at the

time t'_0 . The angle between the neutron trajectory and the X-axis is ψ and a' is the location of the neutron at time t'_0 .

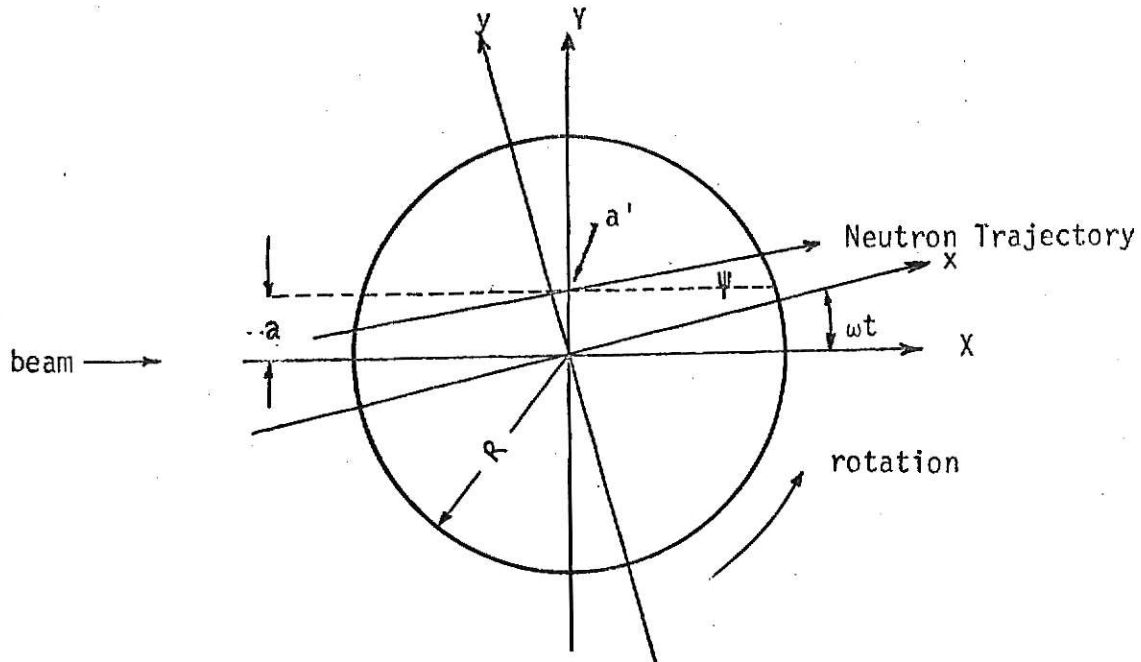


Fig. 1 Laboratory and rotating coordinate systems

In the actual case, neutrons coming out from the beam port of the nuclear reactor are well collimated and they impinge upon the rotor in an almost parallel ($\psi \approx 0$) beam, thus the neutron locus in the X-Y coordinate system can be expressed by

$$X = v(t-t'_0) \quad (1)$$

$$\begin{aligned} Y &= a + x \tan \psi \approx a + \psi x \\ &= a + \psi v(t-t'_0) \end{aligned} \quad (2)$$

where the approximation $\tan \psi \approx \psi$ as $\psi \rightarrow 0$ has been used. Applying the rotation transformation matrix to equations (1) and (2), the neutron locus in the x-y

coordinate system is obtained as

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} v(t-t'_0) \\ a + \Psi v(t-t'_0) \end{bmatrix} \quad (3)$$

Since the ratio of the slit width d to the chopper radius R is much less than unity, the angle of rotation, ωt , of the chopper at time t , is also much less than one. For a constant angular velocity ω , the time available for a neutron to get through the chopper slit is extremely short, thus

$$\begin{aligned} \sin \omega t &\rightarrow \omega t \\ \cos \omega t &\rightarrow 1 \end{aligned} \quad \text{for } \omega t \rightarrow 0$$

Using this condition in the rotation transformation matrix, equation (3) becomes

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 1 & \omega t \\ -\omega t & 1 \end{bmatrix} \begin{bmatrix} v(t-t'_0) \\ a + \Psi v(t-t'_0) \end{bmatrix} \quad (4)$$

Further, the second order term, $\Psi \omega t = (a + \Psi v(t-t'_0))\omega t$, is negligible and may be dropped for a first approximation (confirmation of this will be shown later). Thus equation (4) now has the form

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\omega t & 1 \end{bmatrix} \begin{bmatrix} v(t-t'_0) \\ a + \Psi v(t-t'_0) \end{bmatrix} \quad (5)$$

or

$$\begin{aligned} x &= v(t-t'_0) \\ y &= -\omega t v(t-t'_0) + (a + \Psi v(t-t'_0)) \end{aligned} \quad (6)$$

After eliminating t , equations (6) yield

$$y = -\frac{\omega x^2}{v} + (\psi - \omega t'_0)x + a \quad (7)$$

The above expression represents the neutron motion trajectory in the x - y coordinate system, which is rotating with respect to the X - Y coordinate system. At time $t=0$ the rotor slit is parallel to the neutron beam. When $t = \frac{\psi}{\omega}$, then the tangential line of neutron trajectory is parallel to the rotor slit which makes an angle ψ with the X -axis. Let

$$t_0 = t'_0 - \frac{\psi}{\omega} \quad (8)$$

be the new reference time. Substituting equation (8) into equation (7), yields

$$y = -\frac{\omega x^2}{v} - \omega t_0 x + a \quad (9)$$

It is obvious that the above equation is a downward parabola which describes the neutron motion trajectory in the rotor coordinate system. In the general case, consider the neutron beam which hits the i th slit located at a distance y_0 from the axis of the rotor as shown in Fig. 2. The curved strip represents the region of neutron trajectories which will allow the neutron to leave the slit. Outside that region neutrons will either hit the slit or be caught up to by the slit and will be deleted from the beam.

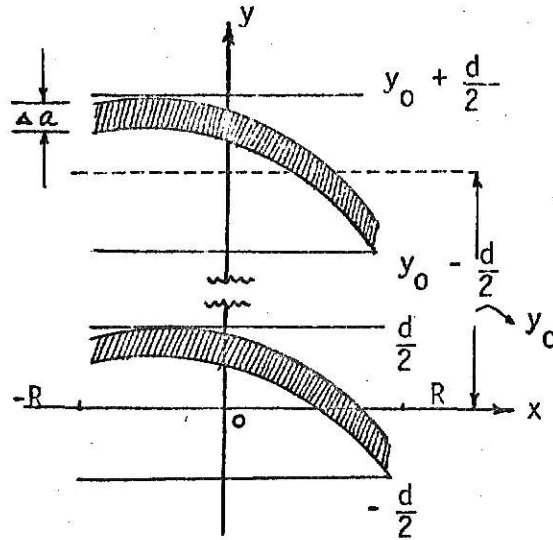


Fig. 2 Neutron motion trajectory in rotor slit system

3.2 Neutron Burst Formation

It is apparent that the y -coordinate has maximum value and minimum value in the interval $-R \leq x \leq R$. Only those neutrons whose y -coordinates lie in the range $y_0 - \frac{d}{2} \leq y \leq y_0 + \frac{d}{2}$ corresponding to $-R \leq x \leq R$, have a chance to pass through the slit. For $t_0 \geq 0$, i.e., neutron in the first quadrant, $y_{\min}$ occurs at $x = R$. Substitution of $x = R$ into the neutron motion trajectory equation (9), yields

$$-\frac{\omega}{v} R^2 - \omega t_0 R + a \geq y_0 - \frac{d}{2} \quad (10)$$

as the first condition for the neutron to pass through the slit. For the second condition there are two possible ways to find the maximum y -coordinate. One is from $-\infty$ up to $-R$ (inclusive) and another from $-R$ to ∞ . The first maximum y -coordinate, $y_{\max}^{(1)}$, is obtained at $x = -R$, since $-R > x$ is outside the

rotor slit and is not of interest here. Then x may be limited to be equal to $x = -R$ for finding of $y_{\max}^{(1)}$. From equation (9), the condition

$$y_{\max}^{(1)} = -\frac{\omega}{v} R^2 + \omega t_0 R + a \leq y_0 + \frac{d}{2} \quad (11)$$

is obtained. By differentiating equation (9), and setting the derivative to zero, $y_{\max}^{(1)}$ is found at $x_m = \frac{-t_0 v}{2}$. The time conditions for a neutron to pass through the slit is thus found to be

$$t_0 > \frac{2R}{v} \quad (12)$$

The second $y_{\max}^{(2)}$ is directly calculated from equation (9) for $x = -\frac{vt_0}{2}$ and

$$y_{\max}^{(2)} = \frac{1}{4} \omega v t_0^2 + a \leq y_0 + \frac{d}{2} \quad (13)$$

must hold. Then another time condition for the neutron to pass through the slit is obtained as

$$0 \leq t_0 \leq \frac{2R}{v} \quad (14)$$

It is customary to normalize the neutron density in burst form passing through the slit under dynamic conditions to the neutron density under stationary conditions. The two different time conditions as shown in equations (12) and (14) are discussed below;

$$\text{Case 1. } t_0 \geq \frac{2R}{v}$$

For those neutrons allowed to pass through the slit, equations (10) and (11) must hold simultaneously

$$\frac{\omega}{v} R^2 + \omega t_o R + y_o - \frac{d}{2} \equiv a_{\min} < a < a_{\max} \equiv \frac{\omega}{v} R^2 - \omega t_o R + y_o + \frac{d}{2}$$

Thus

$$\Delta a \equiv a_{\max} - a_{\min} \equiv d - 2\omega R t_o \quad (15)$$

After normalization

$$f(v, t_o) = 1 - \frac{2\omega R}{d} t_o \quad (16)$$

where $f(v, t_o)$ is defined as the neutron burst with given velocity v for variable time t_o . For physical interest the limiting cases $f(v, t_o) \geq 0$ and $f(v, t_o) \leq 1$, are examined. From equation (16), $t_o \leq \frac{d}{2\omega R}$ must be satisfied. Therefore, equation (16) is true only for

$$\frac{2R}{v} \leq t_o \leq \frac{d}{2\omega R} \quad (17)$$

The time condition $t_o \leq \frac{d}{2\omega R}$ can also be found by multiplying the inequality $t_o \geq \frac{2R}{v}$ by ω . This yields

$$\omega t_o \geq \frac{2R\omega}{v} \quad (\omega > 0)$$

Thus it is observed that the neutron with velocity v makes an angle $\frac{2R}{v}\omega$, which is smaller than the slit angle and the neutron trajectory curve can be com-

pletely fitted into the slit. But when the neutron velocity decreases, $\frac{2R}{v} \omega$ increases. Since the maximum angle of interest is $\frac{d}{2R}$, then the lower limit neutron velocity can be determined, in order that the neutron trajectory curve will fully fit into the slit. This condition is then found to be

$$\frac{d}{2R} \geq t_o \geq \frac{2R}{v} \omega$$

or

$$\frac{d}{2R\omega} \geq t_o \geq \frac{2R}{v} \quad \omega \neq 0 \quad (18)$$

Equations (17) and (18) are identical. This time range exists only for neutrons with velocities lying in the range

$$\omega > v \geq \frac{4\omega R^2}{d} \quad (19)$$

From the above equation, t_o lies in the range

$$\frac{d}{2\omega R} \geq t_o \geq \frac{2R}{v} \quad (20)$$

Now, if equations (11) and (13) ($y_{\max}^{(1)} = y_{\max}^{(2)}$) are equated and solved for t_o , the result is

$$\frac{-\omega}{v} R^2 + \omega t_o R + a = \frac{1}{4} \omega t_o^2 v + a$$

then

$$t_o = \frac{2R}{v}$$

This implies that the expressions of $y_{\max}^{(1)}$ and $y_{\max}^{(2)}$ change form at $t_0 = \frac{2R}{v}$.

Thus the neutron burst $f(v, t_0)$ for t_0 lying between 0 and $\frac{2R}{v}$ can be found.

$$\frac{\omega R^2}{v} + \omega t_0 R + y_0 - \frac{d}{2} \equiv a_{\min} \leq a \leq a_{\max} \equiv y_0 + \frac{d}{2} - \frac{\omega v t_0^2}{4}$$

whence

$$\begin{aligned} f(v, t_0) &= 1 - \frac{\omega R^2}{vd} - \frac{\omega R}{d} t_0 - \frac{\omega v}{4d} t_0^2 = \\ &= 1 - \frac{\omega v}{4d} \left(t_0 + \frac{2R}{v} \right)^2 \end{aligned}$$

Case 2. $t_0 < \frac{2R}{v}$.

The expressions in Case 1 are also valid for the $t_0 < \frac{2R}{v}$ case.

$$f(v, t_0) = 1 - \frac{\omega v}{4d} \left(\frac{2R}{v} + t_0 \right)^2; \quad \text{for } t_0 \leq 2\sqrt{\frac{d}{\omega v}} - \frac{2R}{v}$$

where $f(v, t_0)$ is not a negative quantity. For a non-zero value of $f(v, t_0)$, v must be in the range

$$\frac{4\omega R^2}{d} \geq v \geq \frac{\omega R^2}{d}$$

If $\frac{\omega R^2}{d} > v$, $f(v, t_0) < 0$ for any value of t_0 . Thus

$$v_{\text{cut}} = \frac{\omega R^2}{d}$$

is called the neutron cut-off velocity below which no neutron transmission is possible. For possible neutron transmission, $v > \frac{\omega R^2}{d}$ or

$$\frac{v}{\omega} > \frac{R}{d} R \quad \text{since } R \gg d \geq Y \text{ and } \frac{R}{d} \gg 1$$

thus $\frac{v}{\omega} \gg Y$. Therefore, the validity of neglecting $Y\omega t$ in equation (4) is established.

Another important parameter connected to the neutron cut-off velocity is the neutron maximum flight path, $L_{\max}$. $L_{\max}$ is defined as the distance required for the slowest neutron to reach the detector before the next neutron burst starts at a given angular velocity ω . It is easily shown that

$$L_{\max} = \frac{\pi R^2}{d}$$

Up to this point, t_0 is confined, $t_0 \geq 0$. A change of sign of t_0 is obviously equivalent to a change of x-axis direction and does not affect the neutron's possibility of escaping the absorption from the slit. Therefore

$$f(v, t_0) = f(v, |t_0|)$$

Finally, the complete expressions of the neutron burst function $f(v, t_0)$ are summarized below;

Case 1. $\omega > v \geq \frac{4\omega R^2}{d}$

$$f(v, t_0) = 0 \quad ; \quad t_0 \leq \frac{-d}{2\omega R} \quad (21a)$$

$$f(v, t_0) = 1 + \frac{2\omega R}{d} t_0 \quad ; \quad \frac{-d}{2\omega R} \leq t_0 \leq \frac{-2R}{v} \quad (21b)$$

$$f(v, t_0) = 1 - \frac{\omega v}{4d} \left(\frac{2R}{v} - t_0 \right)^2 \quad ; \quad \frac{-2R}{v} \leq t_0 \leq 0 \quad (21c)$$

$$f(v, t_0) = 1 - \frac{\omega v}{4d} \left(\frac{2R}{v} + t_0 \right)^2 \quad ; \quad 0 \leq t_0 \leq \frac{2R}{v} \quad (21d)$$

$$f(v, t_0) = 1 - \frac{2\omega R}{d} t_0 \quad ; \quad \frac{2R}{v} \leq t_0 \leq \frac{d}{2\omega R} \quad (21e)$$

$$f(v, t_0) = 0 \quad ; \quad \frac{d}{2\omega R} \leq t_0 \quad (21f)$$

Case 2. $\frac{4\omega R^2}{d} \geq v \geq \frac{\omega R^2}{d}$

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THAT ARE CROOKED
COMPARED TO THE
REST OF THE
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$$f(v, t_0) = 0 \quad ; \quad t_0 \leq -2\sqrt{\frac{d}{\omega v}} + \frac{2R}{v} \quad (21g)$$

$$f(v, t_0) = 1 - \frac{\omega v}{4d} \left(\frac{2R}{v} - t_0 \right)^2 \quad ; \quad -2\sqrt{\frac{d}{\omega v}} + \frac{2R}{v} \leq t_0 \leq 0 \quad (21h)$$

$$f(v, t_0) = 1 - \frac{\omega v}{4d} \left(\frac{2R}{v} + t_0 \right)^2 \quad ; \quad 0 \leq t_0 \leq 2\sqrt{\frac{d}{\omega v}} - \frac{2R}{v} \quad (21i)$$

$$f(v, t_0) = 0 \quad ; \quad 2\sqrt{\frac{d}{\omega v}} - \frac{2R}{v} \leq t_0 \quad (21j)$$

Fig. 3 shows the shape of a neutron burst for three different velocity ranges.

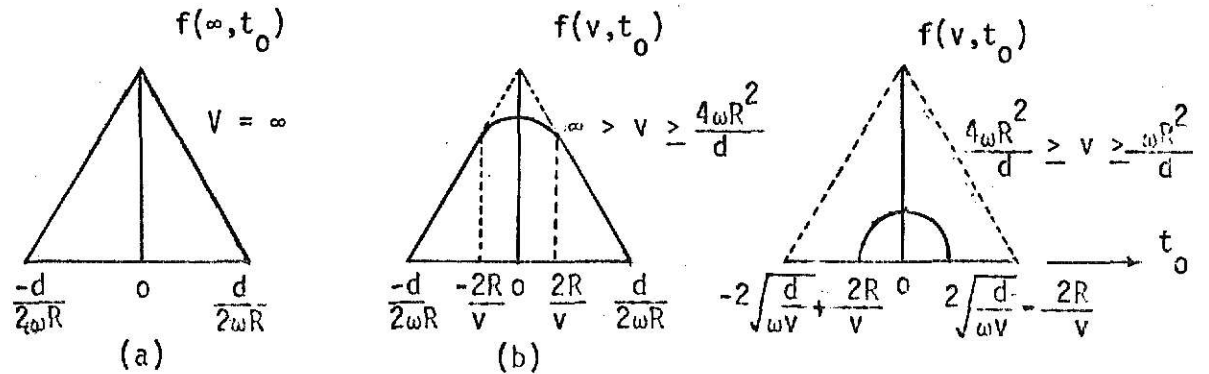


Fig. 3 Shape of the neutron burst for different velocity ranges

From Fig. 3 the neutron burst duration can be determined. In Fig. 3a, the neutron burst duration for infinite velocity neutron is $T_n = \frac{d}{\omega R}$. For neutrons which have velocities in the range $\infty > v \geq \frac{4\omega R^2}{d}$, $T_n = \frac{d}{\omega R}$ which is not a function of neutron velocity v . For the range $\frac{4\omega R^2}{d} \geq v \geq \frac{\omega R^2}{d}$, T_n is found as

$$T_n = 4\sqrt{\frac{d}{\omega v}} - \frac{4R}{v} \quad (22)$$

which does depend on neutron velocity v . Putting $v = \frac{4\omega R^2}{d}$ and $\frac{\omega R^2}{d}$ into equation (22) respectively, T_n is found to lie in the range

$$\frac{d}{\omega R} \geq T_n \geq 0 \quad (23)$$

The neutron cut-off velocity can also be obtained by letting $T_n = 0$ in equation (22)

$$v_{\text{cut}} = \frac{\omega R^2}{d}$$

So far concerning T_n , the neutron burst duration, it is assumed that a parallel neutron beam impinges on the slit. If the beam spreads out over an angle 2ϕ , then the neutron burst durations are given as below;

$$T_n = \frac{d}{\omega R} + \frac{2\phi}{\omega} \quad \infty > v \geq \frac{4\omega R^2}{d} \quad (24)$$

$$T_n = 4\sqrt{\frac{d}{\omega v}} - \frac{4R}{v} + \frac{2\phi}{\omega};$$

$$\frac{4\omega R^2}{d} \geq v \geq \frac{\omega R^2}{d} \quad (25)$$

3.3 Rotor Transmission

Designate $J(v) = \int_{t_0}^{\max} f(v, t_0) dt_0$ as the slit transmission function.

It is clear that $J(v)$ equals the areas of shapes of Fig. 3b and Fig. 3c and represent the total number of given neutrons transmitted. After integrating equations (21) over the appropriate time intervals, $J(v)$ has the form (see APPENDIX B).

$$J(v) = \frac{d}{2\omega R} \left(1 - \frac{8\omega 2R^4}{3d^2 v^2}\right) \quad \text{for } \infty > v \geq \frac{4\omega R^2}{d} \quad (26)$$

$$J(v) = \frac{d}{\omega R} \left(\frac{4\omega^2 R^4}{3d^2 v^2} - \frac{4\omega R^2}{dv} + \frac{8\omega R}{3d} \sqrt{\frac{d}{\omega v}} \right)$$

$$\text{for } \frac{4\omega R^2}{d} \geq v \geq \frac{\omega R^2}{d} \quad (27)$$

It is convenient to normalize the slit transmission function $J(v)$, as V. I. Mostovoi et al.,⁽¹²⁾ suggested. $J(v)$ is divided by the slit transmission at infinite neutron velocity $J(\infty)$. From Fig. 3a, $J(\infty)$ is simply equal to the triangular area $\frac{d}{2\omega R}$. Upon such a normalization

$$J(v) = 1 - \frac{8\omega^2 R^4}{3v^2 d^2} \quad \text{for } \infty > v \geq \frac{4\omega R^2}{d} \quad (28)$$

$$J(v) = \frac{8\omega^2 R^4}{3v^2 d^2} - \frac{8\omega R^2}{vd} + \frac{16\omega R}{3d} \cdot \sqrt{\frac{d}{\omega v}}$$

$$\text{for } \frac{4\omega R^2}{d} \geq v \geq \frac{\omega R^2}{d} \quad (29)$$

For simple expression of $J(v)$ by introducing $x = R\sqrt{\frac{\omega}{dv}}$, $J(v)$ has the compact form

$$J(x) = 1 - \frac{8}{3} x^4 \quad \text{for } 0 \leq x \leq \frac{1}{2} \quad (30)$$

$$J(x) = \frac{16x}{3} \left(1 + \frac{x}{2}\right) (1 - x)^2 \quad \text{for } \frac{1}{2} \leq x \leq 1 \quad (31)$$

Plots of $J(x)$ for two different x 's are shown in Fig. 4. It is observed that a revolving chopper slit does not transmit neutrons of different velocities equally. It is also indicated that in the measurement of reactor neutron spectrum, one should take the value of x less than 0.5 in order to obtain

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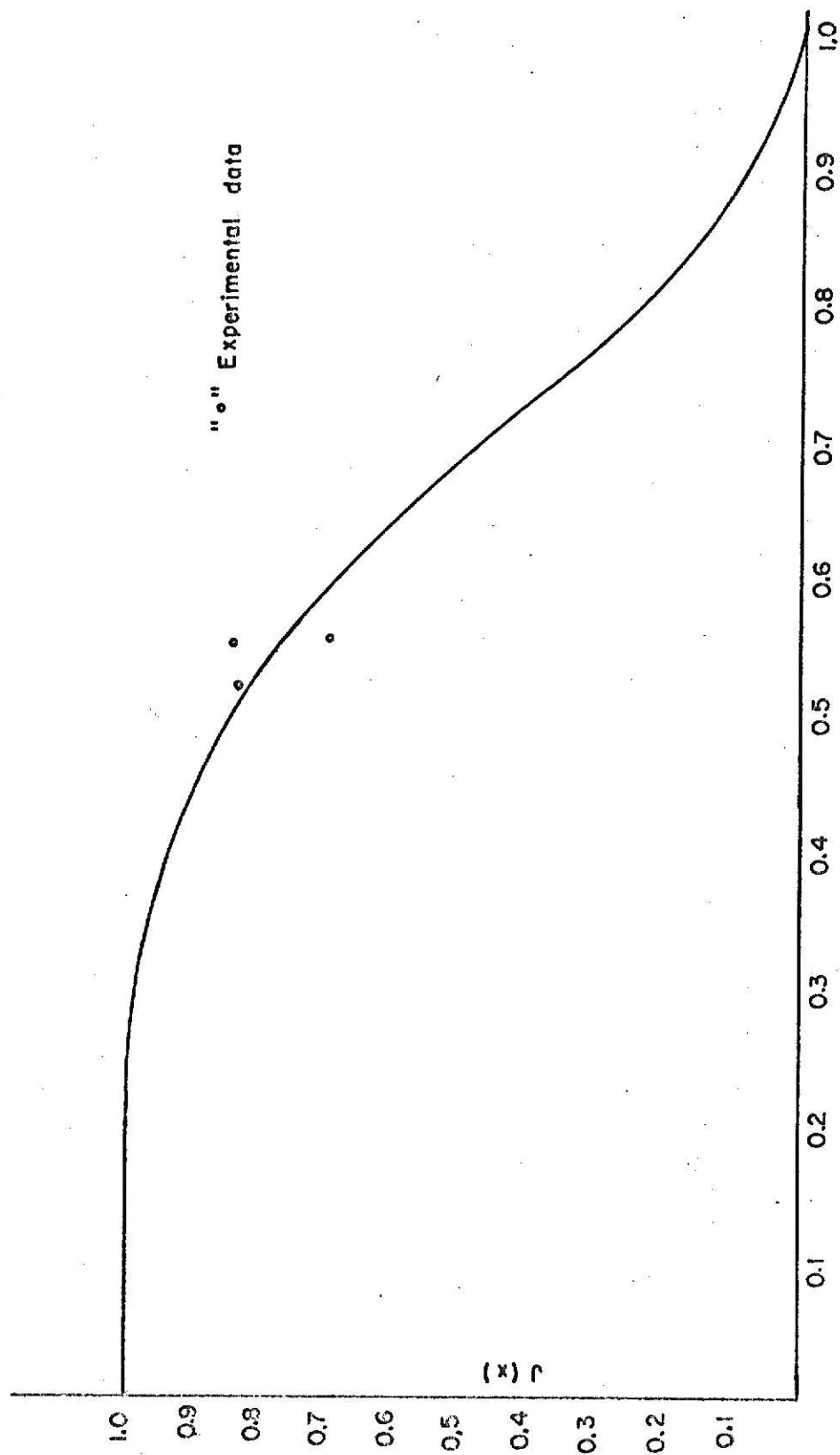


Fig.4 Slit transmission curve

approximately equal transmission of neutrons of all velocities. The most important application of $J(x)$ is to correct the measured spectrum to obtain the true relative neutron spectrum incident on the slit.

3.4 System Resolution

A straightforward definition of system resolution is defined as the fractional timing uncertainty in the time-of-flight, T_{fl} , and is the sum of several fractional timing uncertainties and flight path uncertainties. These uncertainties are

Timing uncertainties; a. time duration of neutron burst
b. channel length in time analyzer
c. neutron time-of-flight in detector, and
d. detector "jitter"

Flight path uncertainties;
e. neutron path in the detector, and
f. Flight path uncertainty in the point of starting neutron and the detection of neutron

According to the definition of resolution, it is found to be of the form

$$R' = \frac{\Delta t'}{t_{fl}} + \frac{\Delta L}{L} \quad (32)$$

where $\frac{\Delta t'}{t_{fl}}$ = total timing uncertainties and $\frac{\Delta L}{L}$ = total flight path uncertainties. These uncertainties, except a, and b, are difficult to determine and their effects on the time-of-flight are considered to be negligible. Upon such a simplification, equation (32) becomes simply

$$R' = \frac{\Delta t}{t_{fl}} \quad (33)$$

where Δt only consists of contributions from the time duration of the neutron burst and the channel length uncertainties. Strictly speaking Δt is not simply a summation of the time uncertainty of the neutron burst and the channel length. They are actually of a mathematical convolution integral form. In order to carry out the convolution integral the following simplifying assumptions are made; The shape of the neutron burst for a given velocity can be represented by a triangle with base equal to T_n and the channel length is described by a rectangle $D(t)$ as shown in Fig. 5.

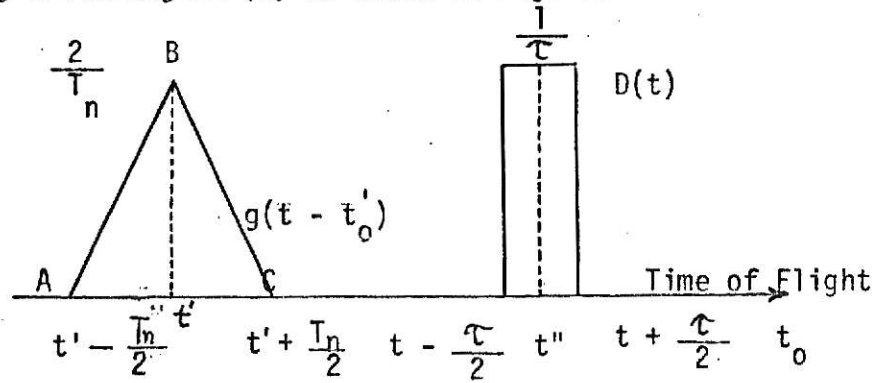


Fig. 5 Time uncertainties

where t is defined as the channel length in the multi-channel analyzer, t' is the center of time duration of the neutron burst (in realistic case, i.e., zero-time, $t' = 0$), and $t'' - t' = T_{fl}$, the time-of-flight. Then Δt ^{(11),(12)} is expressed as

$$\Delta t = \frac{2T_n + \tau}{4T_{fl}} \quad ; \quad T_n > \frac{5}{2} \tau \quad (34)$$

$$\Delta t = T_n + \tau - \sqrt{\tau(2T_n - \tau)} \quad ; \quad T_n < \frac{5}{2} \tau$$

Finally, the resolution R' is

$$R' = \frac{2T_n + \tau}{4T_{fl}} \quad ; \quad T_n > \frac{5}{2}\tau$$

$$R' = \frac{T_n + \tau - \sqrt{\tau(2T_n - \tau)}}{T_{fl}} \quad ; \quad T_n < \frac{5}{2}\tau \quad (35)$$

Equation (35) reveals an important result such that for good resolution, the numerator should be kept as small as possible. Since T_n is only a function of angular velocity ω (see section 3-2) if $\frac{4\omega R}{d} \leq v < \infty$, and τ is channel length, then the optimum resolution condition can be achieved by properly setting ω and τ .

4.0 EXPERIMENTAL APPARATUS

4.1 General Layout

The complete experiments were performed in front of the tangential beam port located in the south side of the reactor bay. The neutron chopper was positioned against a small wood collimator surface. The chopper rotation axis was oriented perpendicularly to the neutron beam. The BF_3 neutron detector was placed at various distances away from the center of the chopper and was oriented perpendicularly to the beam direction. Those neutrons which escape from the BF_3 detector absorption are caught by a beam catcher. A flat semi-circular aluminum table supported the chopper and BF_3 neutron detector and its shielding. Fig. 6 shows a schematic of the top view of the general layout and Fig. 7 shows a block diagram of the electronic equipment (also see Fig. 8 and Fig. 9).

4.2 Mechanical and Electronic Parts

4.2.1 BF_3 Detector^{(13), (14)}

In choosing a neutron detector for measurement of thermal neutron spectrum and total cross-section by time-of-flight method, the following considerations are given;

- a. high detector efficiency
- b. detector timing resolution and timing delay^{(15), (16)}
- c. high ratio of neutron pulse height to gamma pulse height
- d. less temperature, pressure and moisture dependent, and
- e. knowledge of variation of efficiency with incident neutron energy

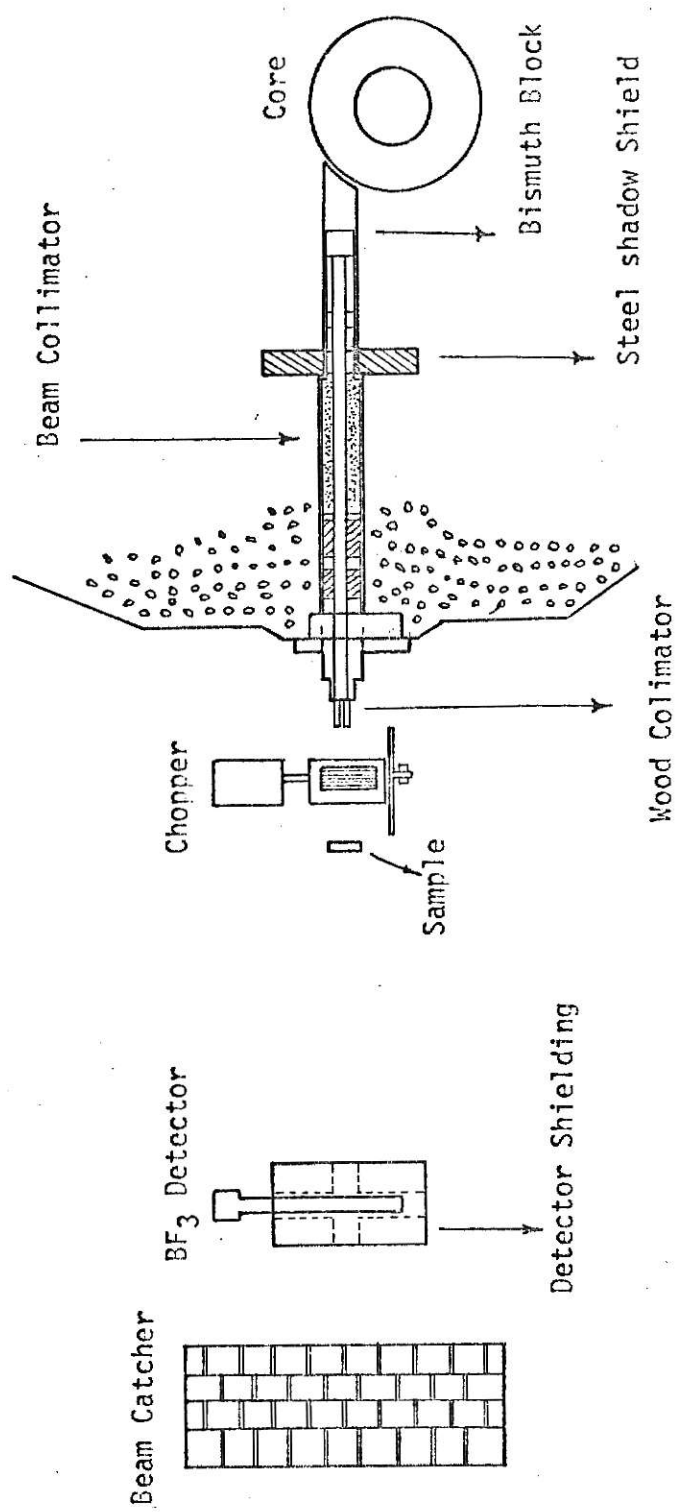


Fig.6 Top view of the layout of experimental apparatus

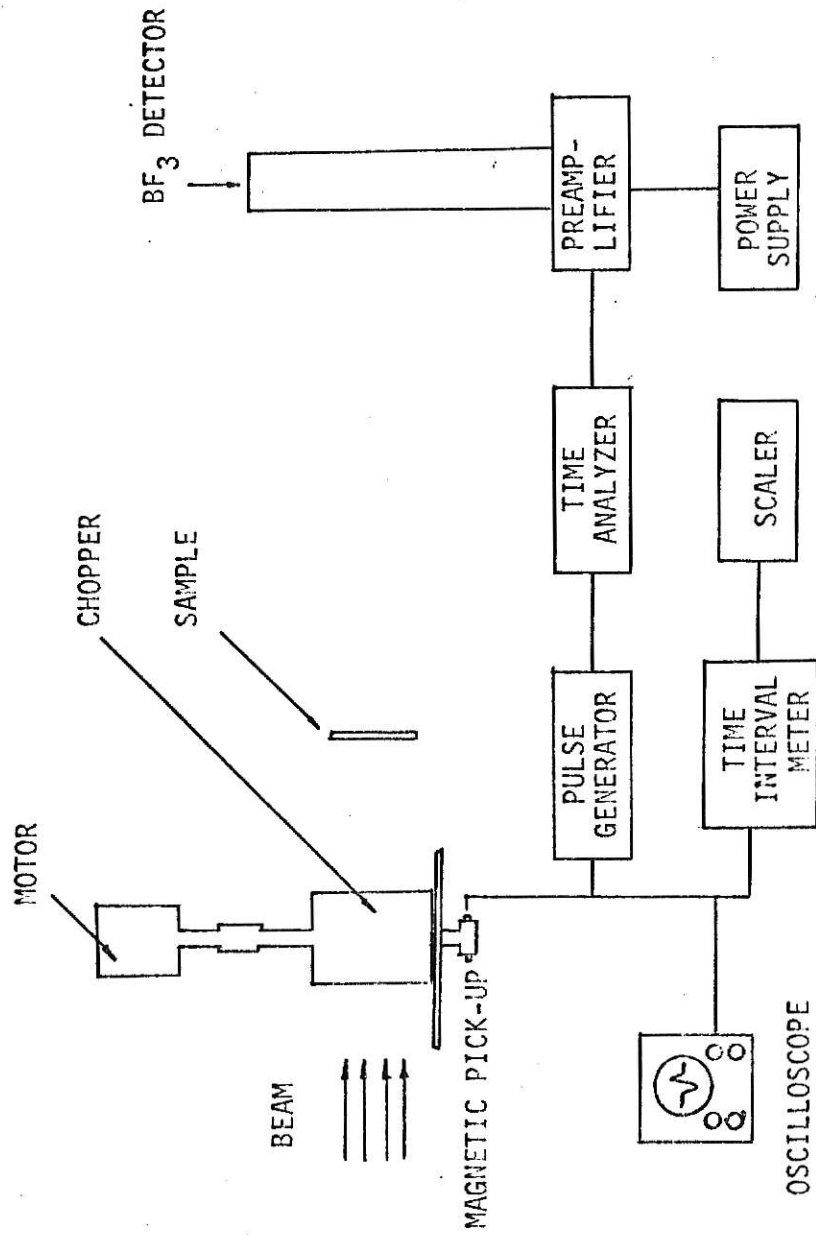


Fig.7 Block diagram of the electronic equipment



Fig. 8 Top view of the experimental apparatus

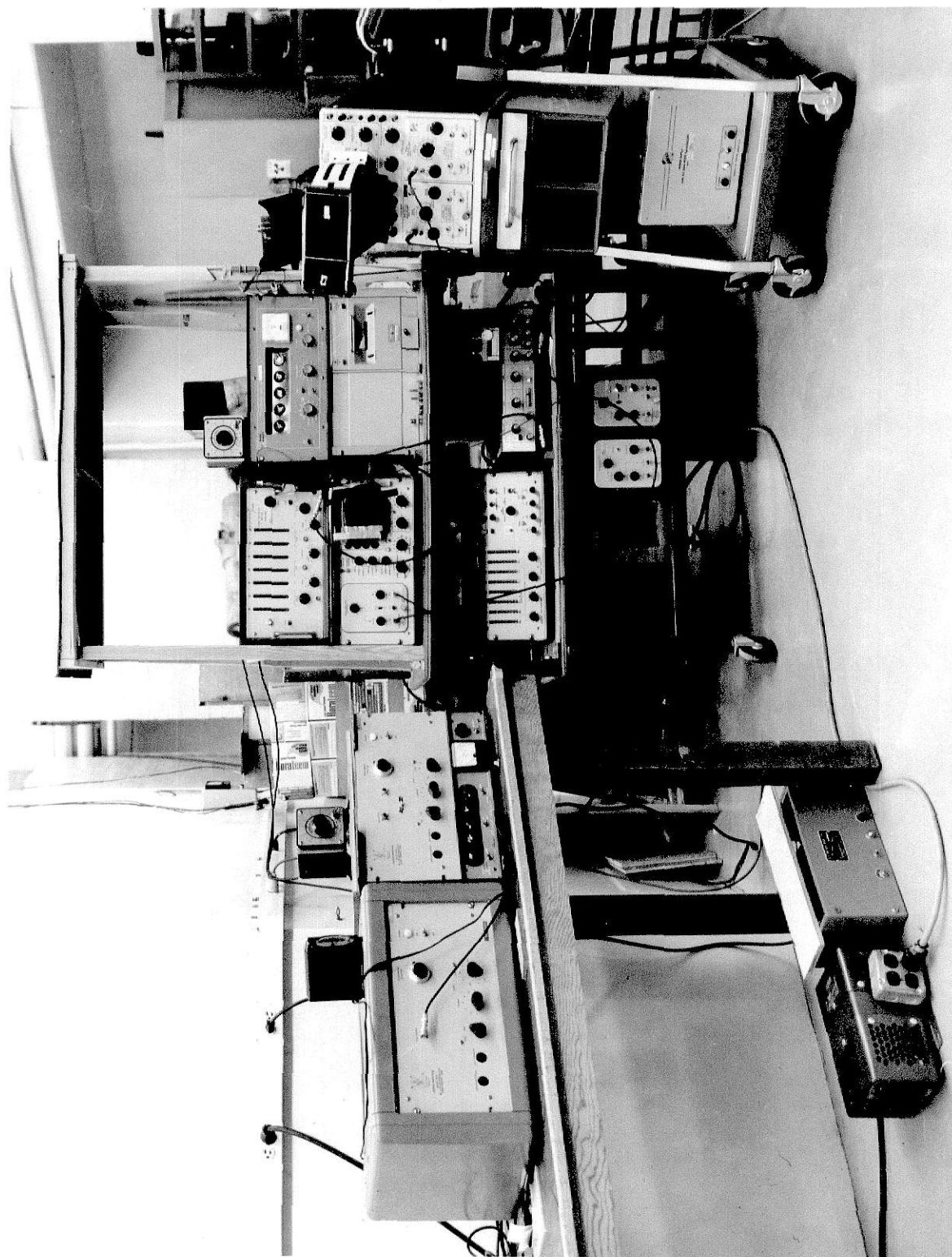


Fig. 9 Instruments

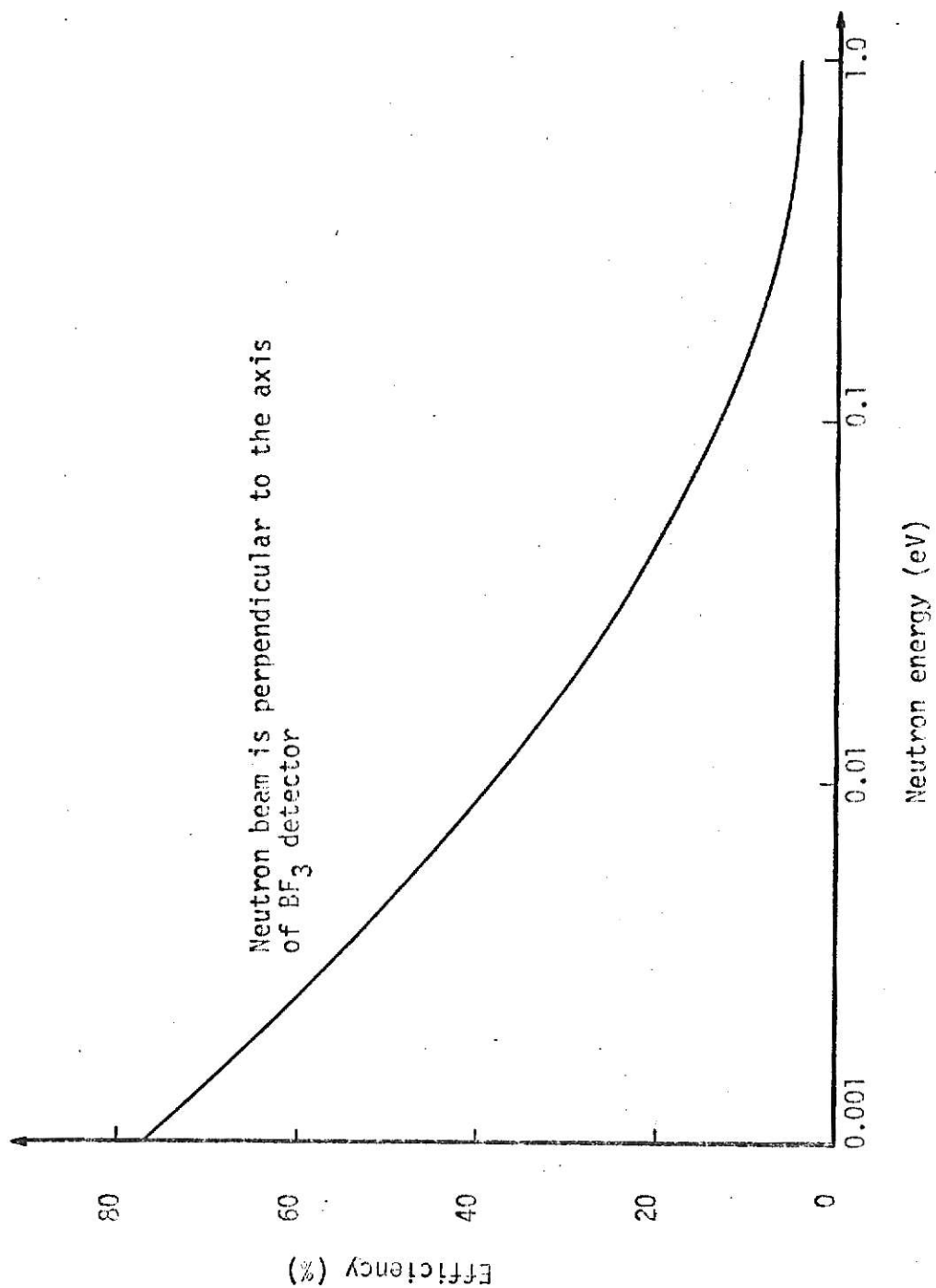
A BF_3 proportional counter, made by N. Wood, with active length $1\frac{1}{2}$ inches and 96% enrichment of B^{10} at pressure 60 cm-Hg was used for this work. A calculated detector efficiency vs neutron energy is shown in Fig. 10.

4.2.2 Detector Shielding

Since aluminum is a very good thermal neutron scatterer as compared to neutron absorption, the incident neutron beam is attenuated mainly due to the neutron scattering process when it passes through the window of the chopper. Those neutrons scattered out of the beam still have some possibility to be scattered back into the beam and counted by detector. In order to avoid these unwanted neutrons from reaching the detector, the detector is inserted in the center opening of a five gallon can filled with a mixture of paraffine and sodium tetraborate decahydrate ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$) by weight ratio 37% and 63% respectively.

4.2.3 Collimator

The collimator was originally designed for performing capture gamma experiments by the Physics Department in this university. Fig. 11 shows the construction of the collimator. An additional one square inch wood collimator with a $\frac{1}{2}$ inch by $\frac{1}{4}$ inch opening in the center was inserted into the main collimator in order to provide the appropriate beam size to the chopper. One $1\frac{1}{2}$ inch by 2 inches by 0.0197 inch cadmium sheet with an opening $\frac{1}{2}$ inch by $\frac{1}{4}$ inch in the center was mounted at one end of the wood collimator, and then placed against the chopper housing window ($\frac{1}{2}$ " x $\frac{1}{4}$ "). With this arrangement, an almost parallel neutron beam incident on the chopper was obtained. A six

Fig. 10 Calculated BF_3 detector efficiency

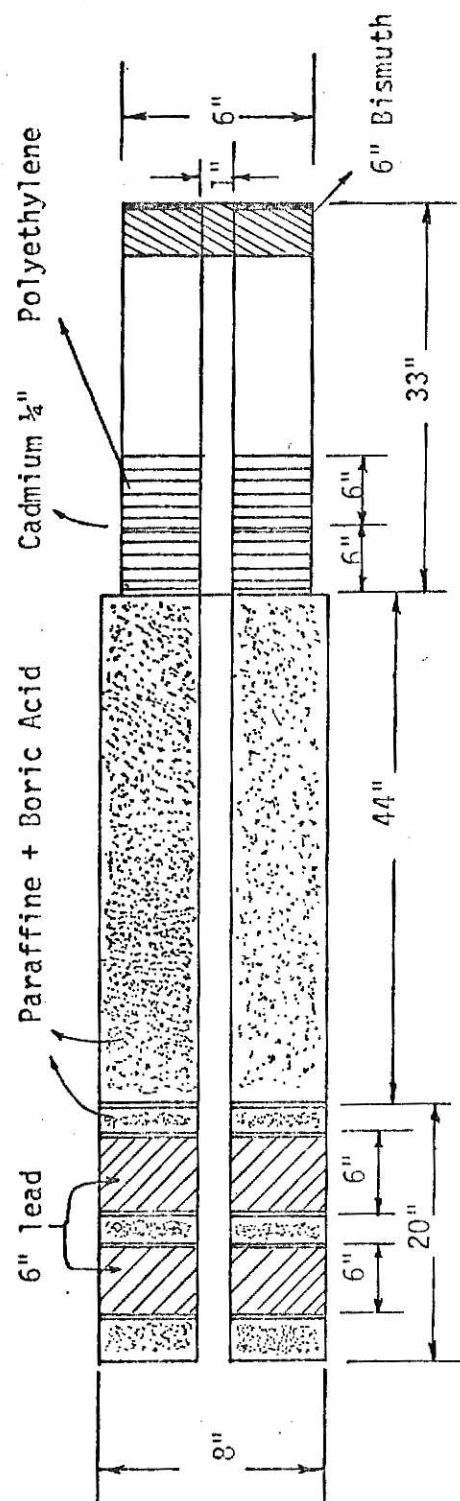


Fig. 11 Main collimator

inch bismuth block is located in the inner end of the main collimator for decreasing the fast-neutron background.

4.2.4 Driving Motor

Two different driving motors have been used for high and low rotation speeds. For low range of rotation the motor used was an A.C. 110 universal type motor, and for high rotation speed, a commercial router motor was used for the best resulting measurement. A line voltage regulator was provided and an ordinary Variac was used to control the above two motor speeds.

4.2.5 Preamplifier

The preamplifier was designed to amplify (gain 120) the millivolts output negative pulse from the neutron detector. The negative pulse output of the preamplifier was connected to the signal input of a multi-channel analyzer having negative 0.3 volts sensitivity. A 20 feet long coaxial cable was used for connection between the multi-channel analyzer and the preamplifier with an accompanying loss in pulse height and increasing pulse rise time. The required power supply is obtained from a BA Multiscaler II Model 132 scaler which also serves as a reactor power level fluctuation indicator during experimental measurements.

4.2.6 Magnetic Pick-Up

The magnetic pick-up (Fig. 12) serves as the chopper rotating position indicator, triggering signal for multi-channel analyzer, and the measurement of angular rotation speed of chopper rotor. It is actuated by two iron tips in

an iron drum (Fig. 13) which is coupled to the rotor shaft. The magnetic pick-up is mounted in a rotary angle indicator (Fig. 14) supported by the chopper housing. This rotary angle indicator is provided for measuring the relative angle between the rotor position where the pulse of the magnetic pick-up occurs and the parallel position of chopper to the neutron beam. The output voltage amplitude primarily depends upon the following factors;

- a. linear velocity of the rotor
- b. clearance between the tip and magnetic pick-up, and
- c. geometrical shape of the iron tip

The output wave form looks like a triangle with the apex slightly rounded off as shown in Fig. 15. Fig. 12 shows the magnetic pick-up in the rotary angle indicator and the iron actuator on the rotor shaft.

4.2.7 Pulse Generator

The pulse generator mainly serves two purposes, one is as a wave shaper, the other for providing delay time between the input signal and output pulse. The output voltage from the magnetic pick-up is connected to the external triggering terminal of the pulse generator. A positive pulse (or negative pulse) with maximum amplitude of 10 volts and the smallest pulse width, 50 nanoseconds, can be obtained. Also, the continuous variable controls of pulse delay and of pulse rise time are provided in this pulse generator so that it makes electronics zero-time determination possible (detailed discussion of technique will be presented later).

In order to reject all external possible noise such as motor sparks between the brushes (which in the beginning caused extra output pulses) the external triggering sensitivity control is set in such a way that the attenuation

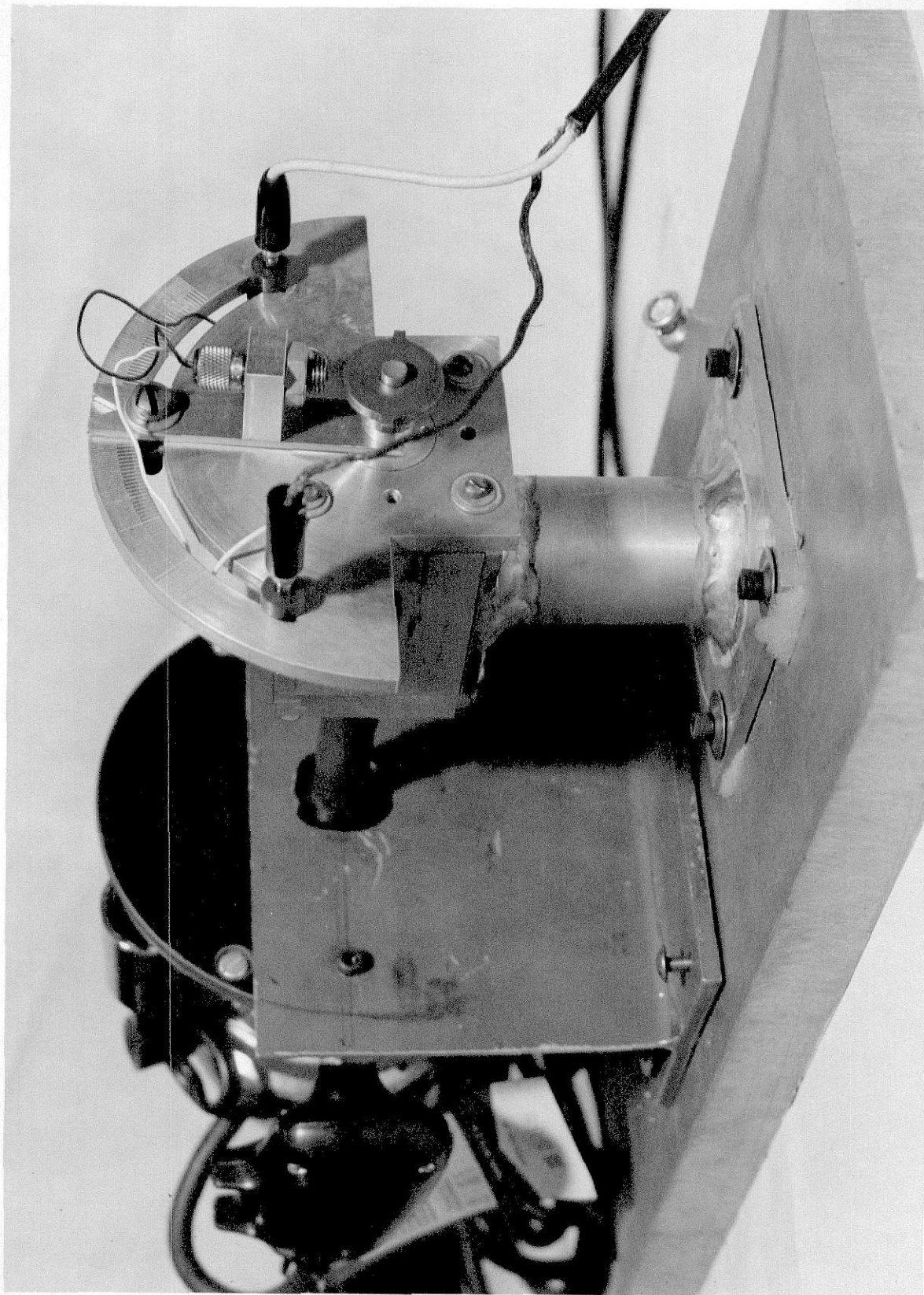
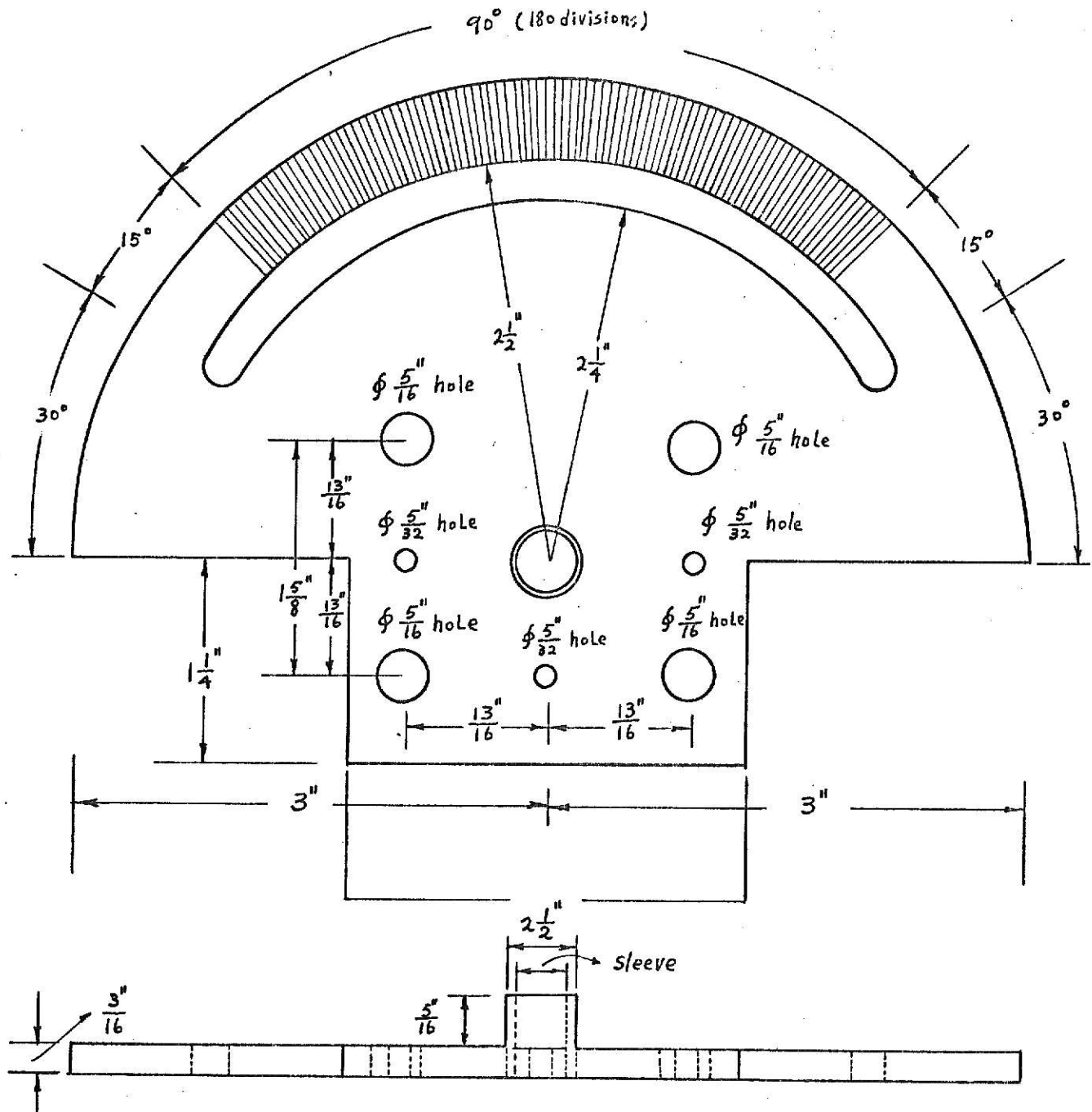


Fig. 12 Magnetic pick-up and rotary angle indicator



Scale 1: 1

- NOTES: 1. Material — aluminum plate
2. Quan. 1

Fig. 14 Rotary angle indicator

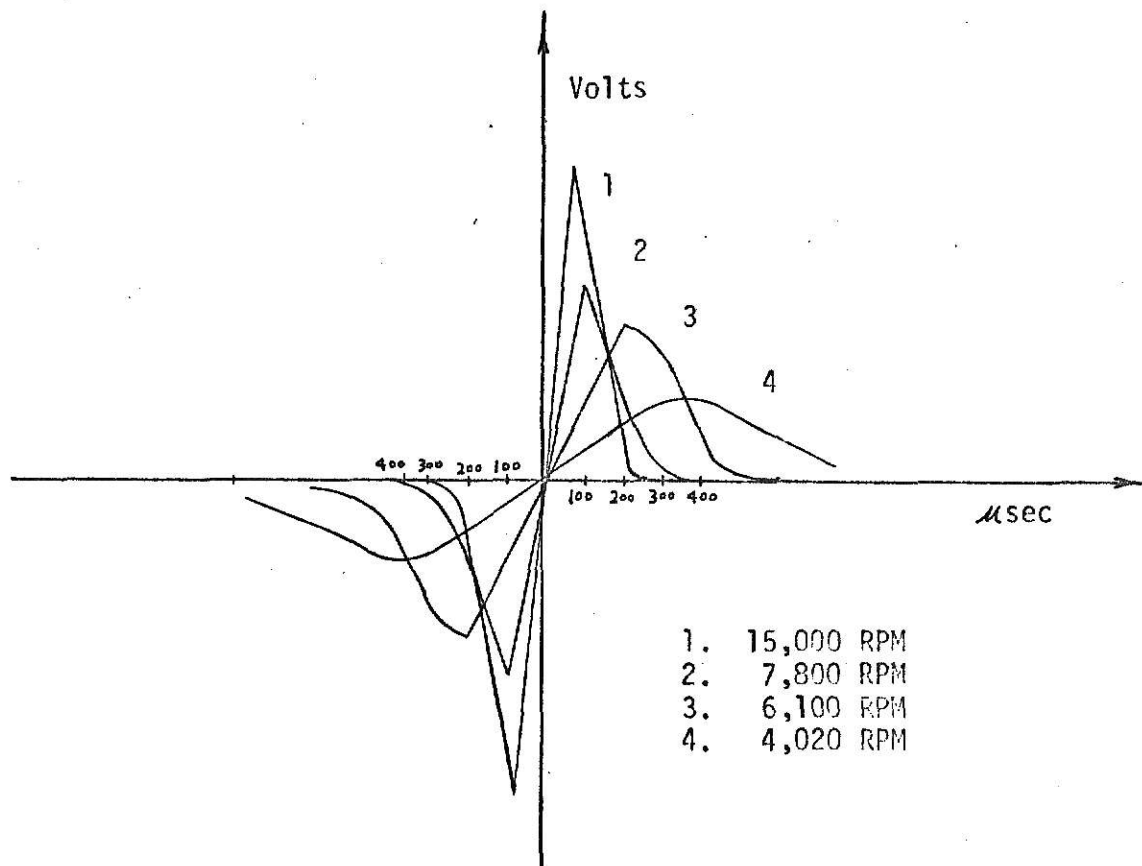


Fig. 15 Output signal of the magnetic pick-up

of the input signal is low enough for triggering the pulse generator. After appropriate setting of all control knobs of the pulse generator a positive 1.5 volts pulse with 50 nanosecond rise time is obtained and fed to the trigger signal input of the multi-channel analyzer for starting counting.

4.2.8 Time Interval Meter

A precise motor rotation period is measured by this time interval meter. It consists of two input pulse forming channels, an oscillator, an electronics gate and a chain of cascaded decimal counting units. The negative-going output voltage of the magnetic pick-up is applied to one of the input channels where it produces a pulse. This pulse thus opens the gate, permitting pulses of the oscillator frequency to pass through and be registered on the decimal counting units. After a certain amount of time, i.e. period, has elapsed, another negative-going output voltage from the magnetic pick-up terminates the gate and stops the counting time. Thus a very accurate motor rotation period is obtained from the decimal counting units. The following Fig. 16 shows how the period is measured.

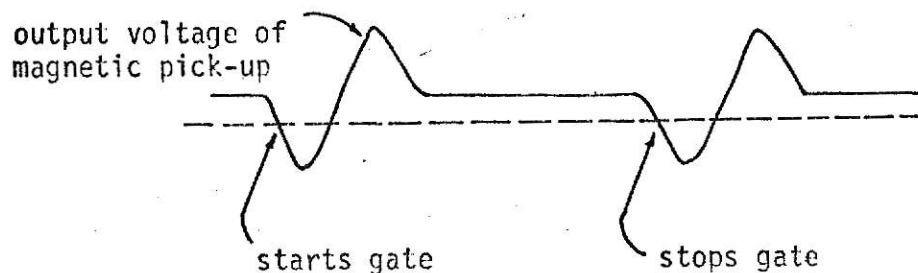


Fig. 16 Schematic of rotor speed pulse timing setup

In addition to the measurement of period, a negative pulse of 10 volts with 0.1 microsecond rise time is provided and is fed to a BA scaler for con-

tinuous motor rotation speed measurement.

4.2.9 TMC Transistorized Multi-channel Pulse Analyzer

In this work, the TMC transistorized multi-channel pulse analyzer system was used. This system primarily consists of three units, CN-110 Digital Computer Unit, 220 Data Output Unit, and Time-of-Flight Plug-in Unit 211. The following is the brief description of operation for these three units;

4.2.9.1 Digital Computer Unit CN-110.⁽¹⁷⁾ This unit is the main part of the system. It contains many different circuits necessary for magnetic data storage; magnetic core with 16x16x16 array size, memory current drive circuits for storage of information and address information, memory cycle control circuits, address and arithmetic binaries, data transfer circuits, binary-to-analog converters, and cathode ray tube for analog display. The CN-110 also provides three different modes of data output, i.e., binary, digital, and analog by appropriate setting of the selector switch in the front panel.

Binary output data is given in form of sixteen-line arithmetic (16 bits has been used) or eight-line arithmetic (8 bits has been used). Digital information is transferred to the 220 series data output unit in the form of a sharp pulse train equal to the registered counts in each individual channel. For analog readout an X-Y or strip chart recorder can be connected to the CN-110 unit for plotting purposes.

4.2.9.2 Data Output Unit 220. The Data Output Unit 220 contains essentially a timing unit and a data handling unit. During the accumulation cycle of the CN-110, the 220 Unit can operate in either a true timing or a live timing mode in three different readout cycles, i.e., manual, semi-automatic and fully-

automatic (destructive or non-destructive and normal or integrated). When the system is set-up for time-of-flight analysis, the 220 Unit serves as a source trigger which starts or stops the CN-110 Unit counting cycle. Preset time and preset count modes are provided for in this unit. A digital printer, Hewlett-Packard HP-561B printer, receives the output of the 220 Unit and prints digital output in an eight column format (3 digits for channel number indication and the other 5 digits for the total counts registered in each channel).

4.2.9. Time-Of-Flight Logic Unit 211. The time-of-flight unit 211 together with the CN-110 unit are able to directly record the neutron wavelength spectrum. This is accomplished by obtaining the arrival time of a pulse produced in the detector by a neutron with respect to the time of release of a given neutron burst over a known flight path length. Nine different channel lengths, i.e., 0.25, 0.5, 1.0, 2, 4, 8, 16, 32, and 64 microseconds can be chosen to perform the desired measurement. The maximum time-of-flight range is from 0.25 to 65,536 microseconds obtained by properly setting the delay time selector switch.

5.0 INITIAL OPERATION AND TEST

5.1 Mechanical Balance and Coupling

During chopper fabrication, efforts were taken to make the chopper as symmetric as possible with respect to the chopper longitudinal axis. A $\frac{1}{4}$ inch polyethylene hose was first used as the coupling between the chopper rotor and the driving motor shaft. When the motor was brought near 16,000 rotations per minute, the polyethylene hose ruptured immediately. Different sorts of hoses and metal wires were tested. Finally, a $\frac{5}{8}$ inch outside diameter by $\frac{3}{16}$ inch wall thickness hose was found to be a suitable coupling material. The chopper was found to be in excellent mechanical balance for continuous 24 hour running at 16,000 rotations per minute.

5.2 Motor Stability Test

A constant rotation speed of the driving motor is desired as one important parameter in this work. A series of 20 second time interval observations of half-period from the Beckman Timer covering one hour was made. These observations reveal that the average motor speed is constant within about 1%. Fig. 17 shows the half-period variation with time for the universal motor and the router motor.

5.3 Rotor Opening Angle

To determine the opening angle of the rotor the chopper rotor was disassembled from the driving motor shaft and a six-inch radius protractor was temporarily mounted on the chopper housing. After the reactor was brought to a 100 Kw power level, the chopper rotor was manually rotated and a one

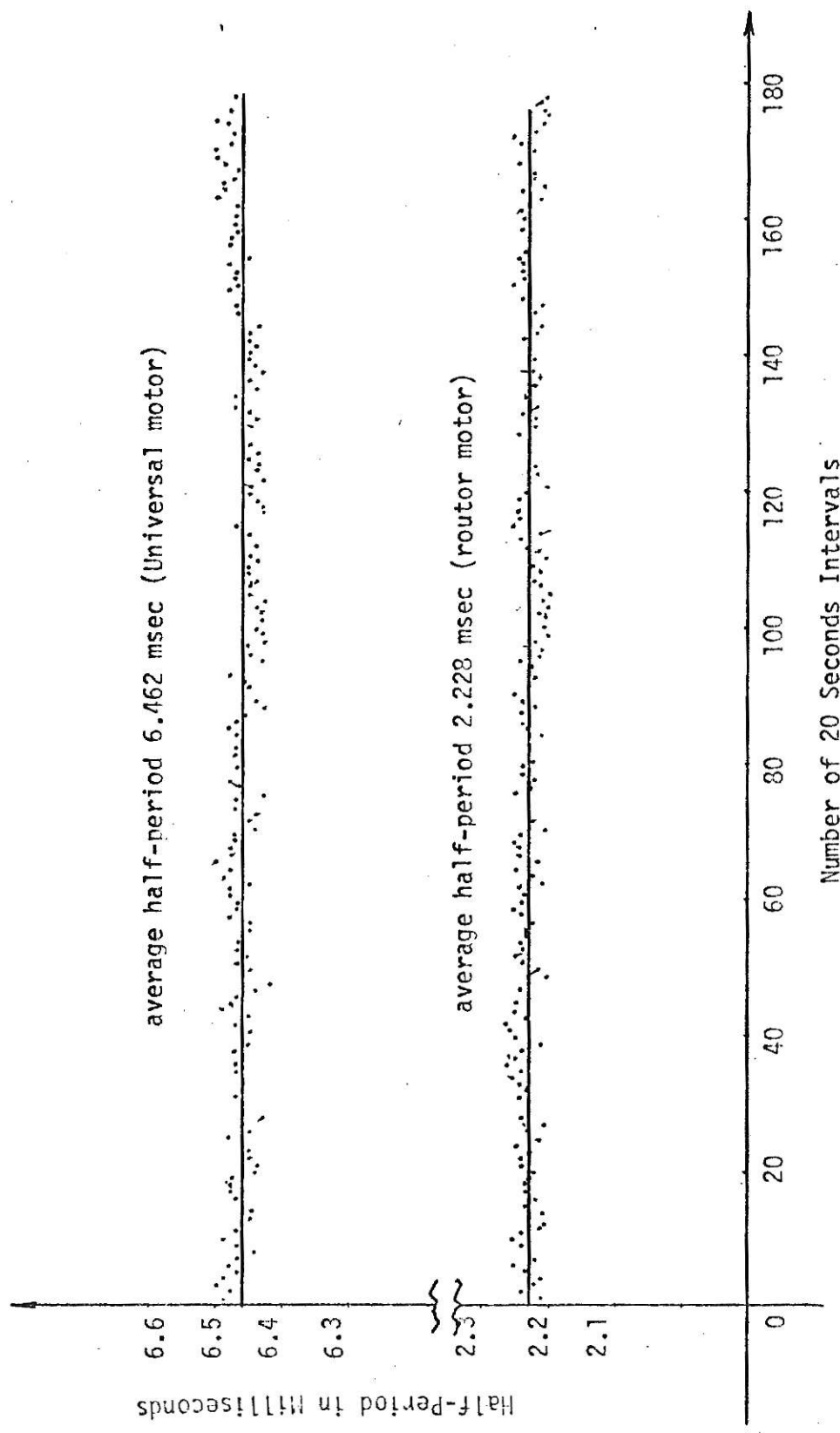


Fig. 17 Motor stability

minute count was made for each different angle. Fig. 18 shows the variation of counting rate from the BF_3 neutron detector versus the chopper rotor angular position. The rotor open angle was found to be 3.9 degrees (vertical plane) and agrees well with the calculated rotor opening angle of 3.925 degrees. The shape shown in Fig. 18 can be considered as similar to a triangle with base R and height d (slit width).

5.4 Electronics Zero-Time Adjustment

Zero-time is usually called reference time in time-of-flight measurements. In this investigation, it was obtained from output of the magnetic pickup actuated by two iron tips in the iron drum rotating with the chopper rotor. When the chopper slit is parallel to the neutron beam, i.e., maximum neutron transmission position, a voltage signal produced by the magnetic pick-up is obtained. The shape of these pulses are shown in Fig. 15. It is obvious that the voltage shape from the magnetic pick-up is strongly dependent on the rotation speed of the chopper rotor. In such a situation, it is evident that the zero-time cannot be independent of angular speed ω . Also the voltage rise time of the magnetic pick-up pulse is too slow compared to the requirement of the triggering signal input of the plug-in logic unit 211. These input requirements are such that the triggering signal input must be positive-going with a rise time less than 0.1 microsecond. Thus an electronic wave shaping circuit is necessary. The following method was applied to meet the above two requirements;

For the chopper opening angle measurement the maximum neutron transmission position was previously found. A mark with respect to chopper housing was made on the chopper rotor, and then the tip of the iron drum and the tip of the magnetic pick-up, which is mounted on a rotary angle indicator arm were lined

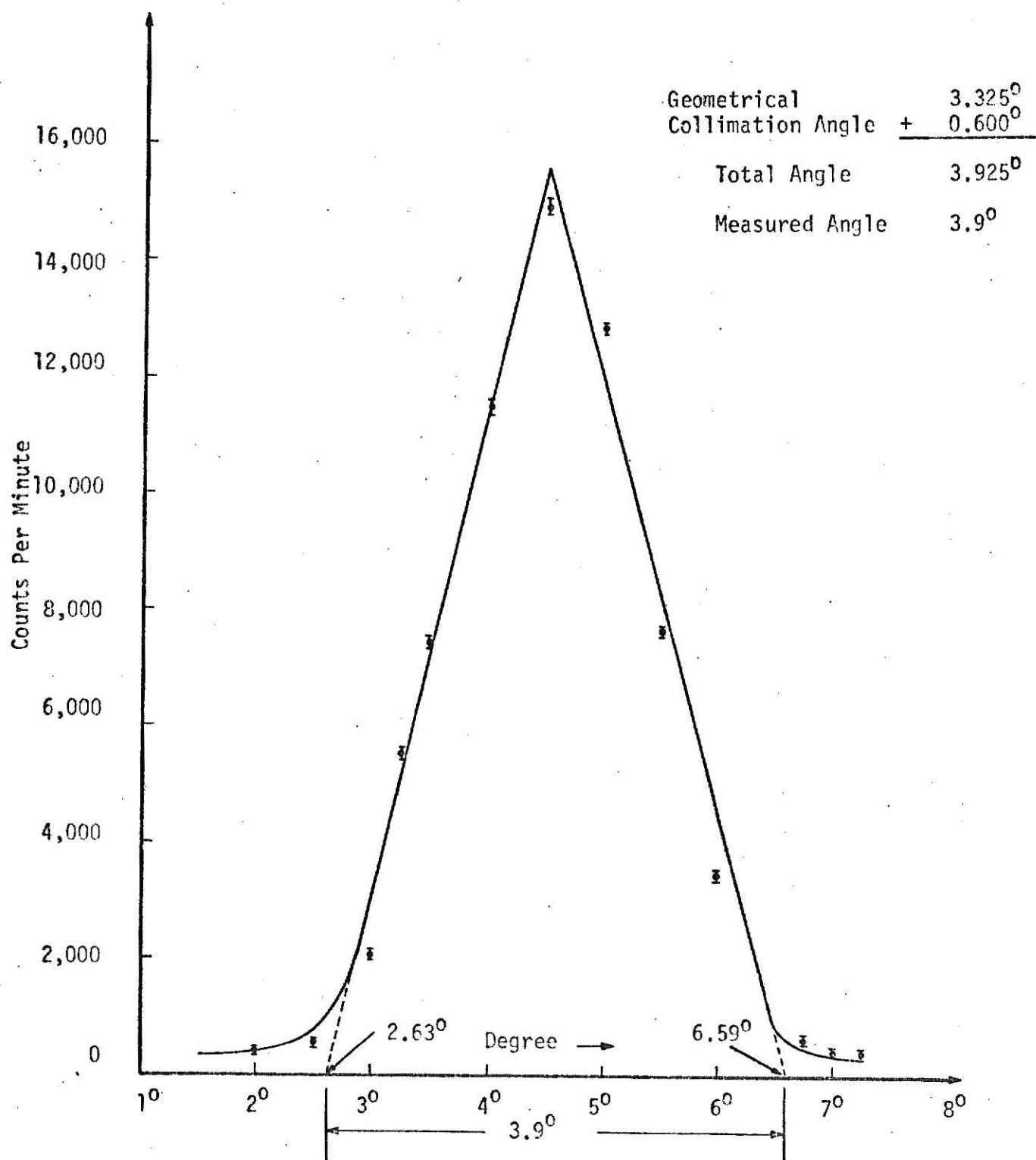


Fig. 18 Rotor opening angle

up. The output of the magnetic pick-up is connected to the input terminal of the pulse generator which provides a 5 nanosecond rise time positive pulse with adjustable amplitude. Both the output voltage from the magnetic pick-up and the positive pulse from the pulse generator are displayed on the dual beam oscilloscope screen (Fig. 19). The positive pulse was carefully adjusted to the point where the magnetic pick-up output signal instantly inverts its polarity from negative to positive-going, i.e., zero crossing point. This adjustment is accomplished by the following means;

- a. changing magnetic pick-up relative angle with respect to the tip of the iron drum--for coarse adjustment, and
- b. changing delay time knob from the pulse generator for fine adjustment.

After such adjustments are done, the positive pulse occurs at exactly zero-time in the time-of-flight scale where the chopper rotor gives the maximum neutron transmission. The pulse can now be fed to the multi-channel analyzer to trigger the gate for duty operation cycle. Fig. 19 shows typical oscilloscope traces which were obtained after setting the electronics zero-time positioning.

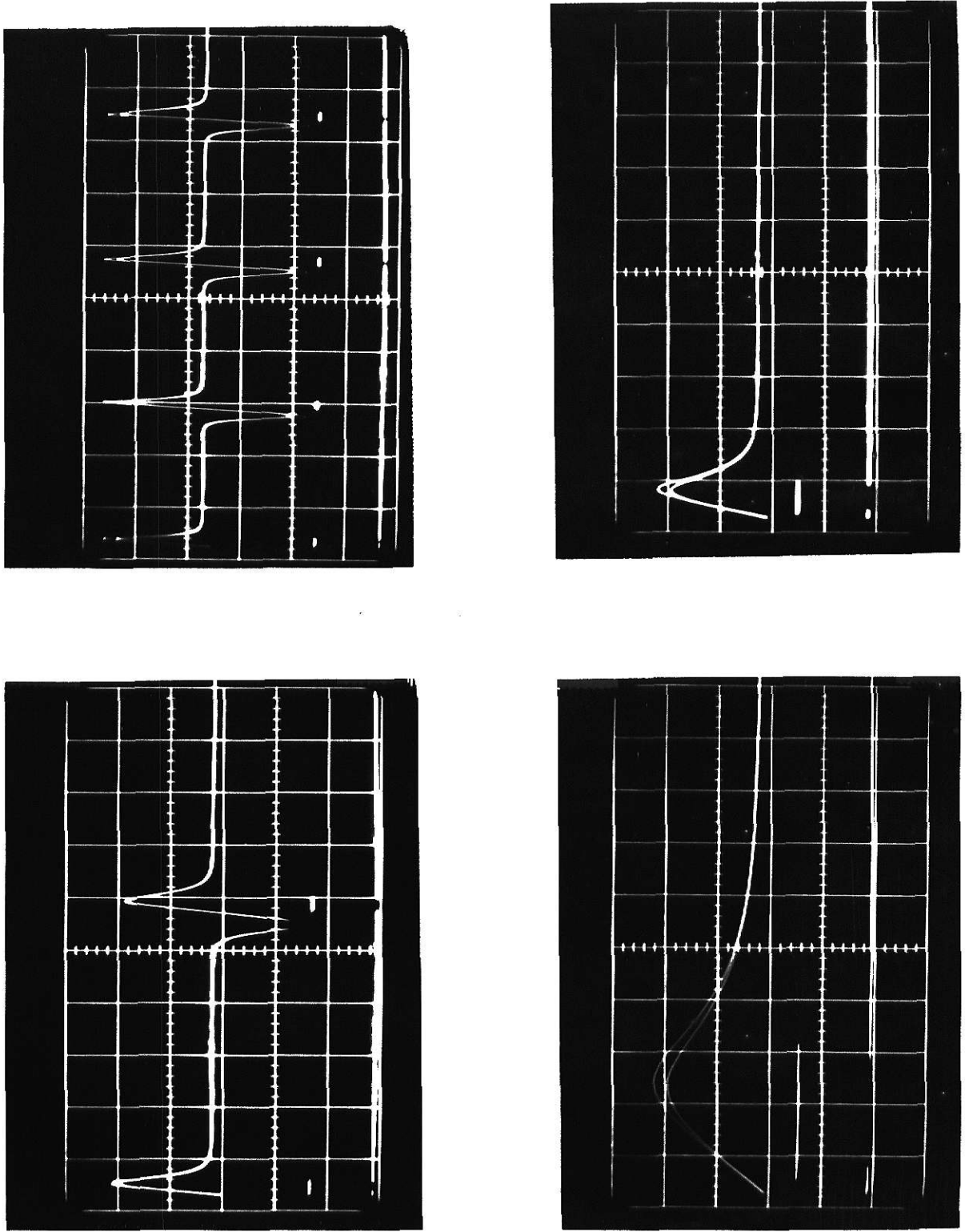


Fig. 19 Electronics zero-time positioning

6.0 RESULTS

6.1 Background

There are three different sources of background that must be accounted for in the time-of-flight data. The first one, the most important contribution to the background, is due to the epi-cadmium neutrons contained in the incident beam. These epi-cadmium neutrons are only slightly attenuated by the rotor when they impinge on it. The second source of background is due to the area background. This source of neutrons are those which scatter from the structures in the reactor bay and reach the BF_3 detector from all directions. This background varies with the experimental environment and can be minimized by using BF_3 detector shielding as described in section 4.2.2. The last source is the multi-scattered neutrons which originally scattered out of the beam and finally recoiled back into the beam. In this investigation, the background due to these multi-scattered neutrons was considered negligible. A background spectrum of time-of-flight was measured by inserting a thin cadmium plate between the collimator and the chopper. Fig. 20 shows the typical background spectrum obtained in the time-of-flight unit. The total background is quite small compared to the observed counting per channel without the cadmium plate placed in front of the chopper.

6.2 Measured Spectrum

During the measurement, various different experimental conditions were investigated in order to compare the effects of several parameters. These different corrections; the analyzer dead time correction⁽²³⁾, the background correction, and the neutron chopper window and BF_3 detector self-shielding

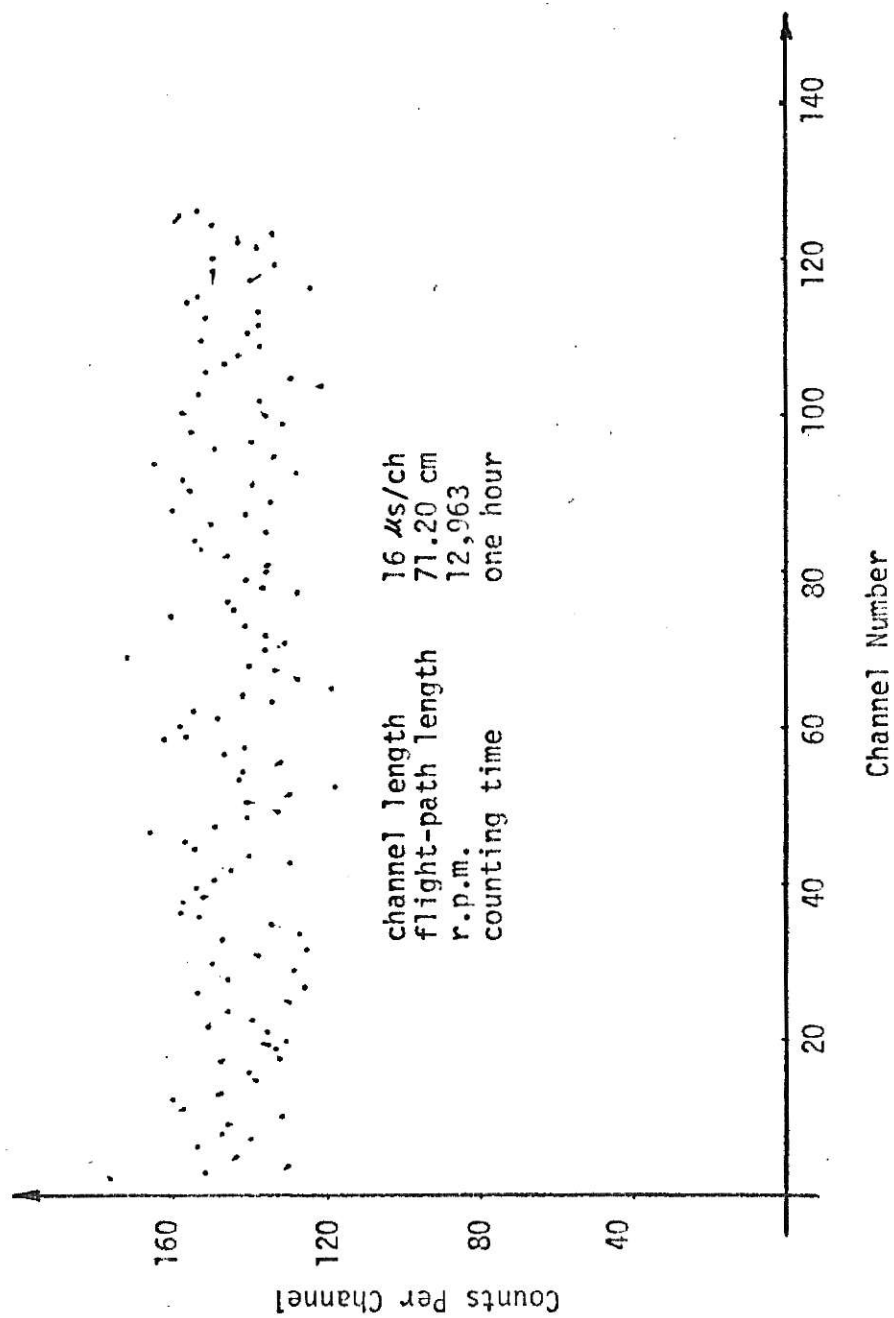


Fig. 20 Background spectrum

effect correction were applied to the original data recorded by the multi-channel analyzer (compare Fig. 21 and Fig. 22). No correction for neutron absorption and scattering in the air path between the collimator and BF_3 detector was made because of the short flight path. Fig. 23 through Fig. 28 show the observed neutron spectrum for different experimental conditions.

The theoretical Maxwellian velocity distribution $n(v)dv \propto v^2 \exp(-\frac{v}{v_0})^2 dv$ (18) was expressed as a function of time-of-flight (or wavelength);

$$n(t)dt \propto t^{-4} \exp(-\frac{t_0}{t})^2 dt$$

where t_0 is the time corresponding to the most probable neutron velocity. The observed values for this time range from 370 $\mu\text{s/m}$ to 425 $\mu\text{s/m}$ corresponding to a range for the most probable neutron velocity from 2700 m/s to 2,360 m/s.

6.3 Experimental Determination of Transmission Function

By definition, the transmission of monoenergetic neutrons is simply

$$\text{Transmission} \equiv \frac{I(E)}{I_0(E)}$$

where $I(E)$ and $I_0(E)$ are the neutron intensities of the transmitted and incident beams at monoenergetic energy E respectively. The calculation is quite straightforward. In principle, with a known incident neutron spectrum $I_0(E)$, the desired transmission function can be obtained from the transmitted neutron spectrum $I(E)$ at a given rotor angular velocity ω . Unfortunately, there is no way to determine the incident neutron spectrum unless it is obtained by

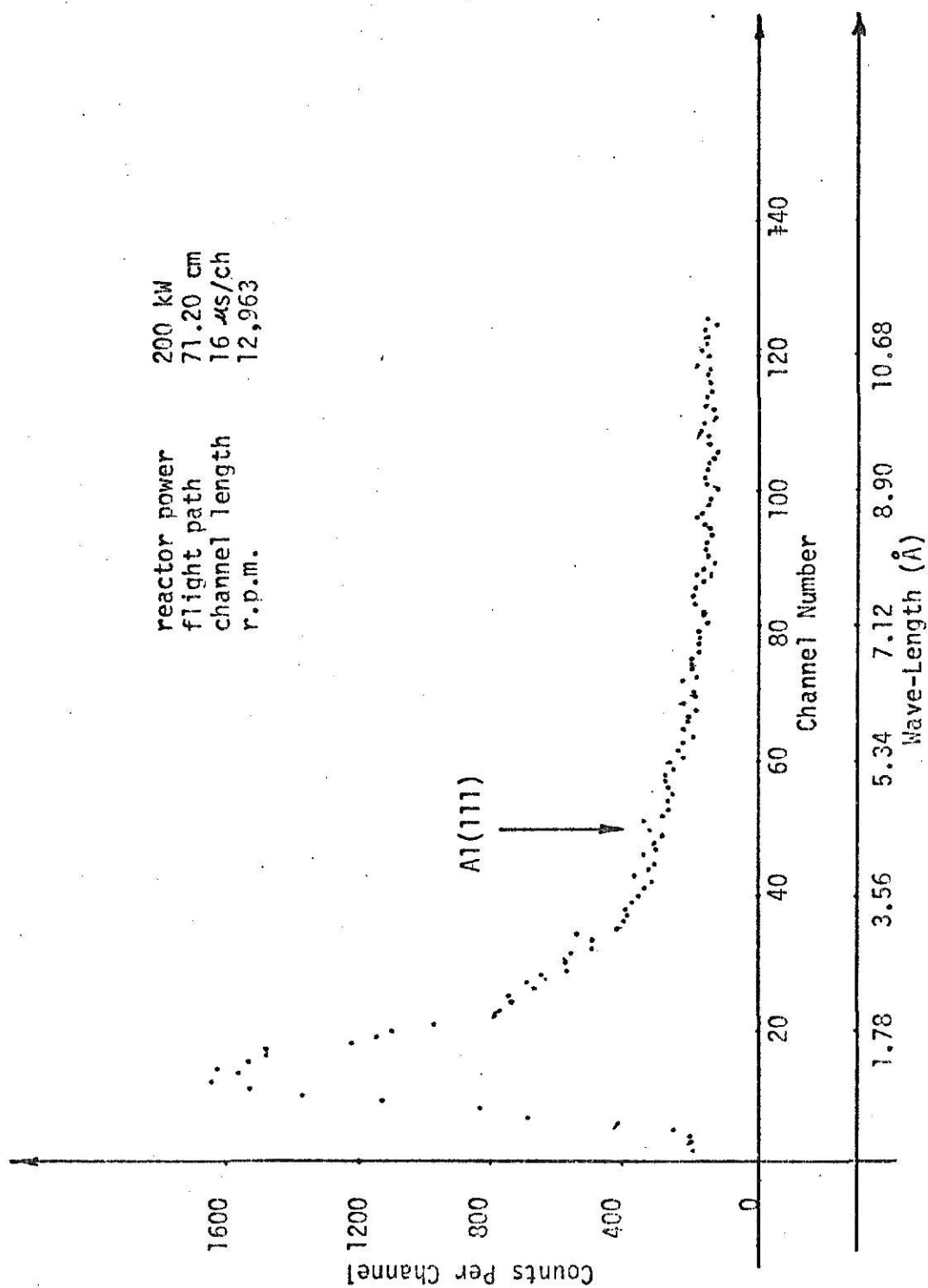


Fig. 21 Time-of-flight spectrum as recorded by the analyzer

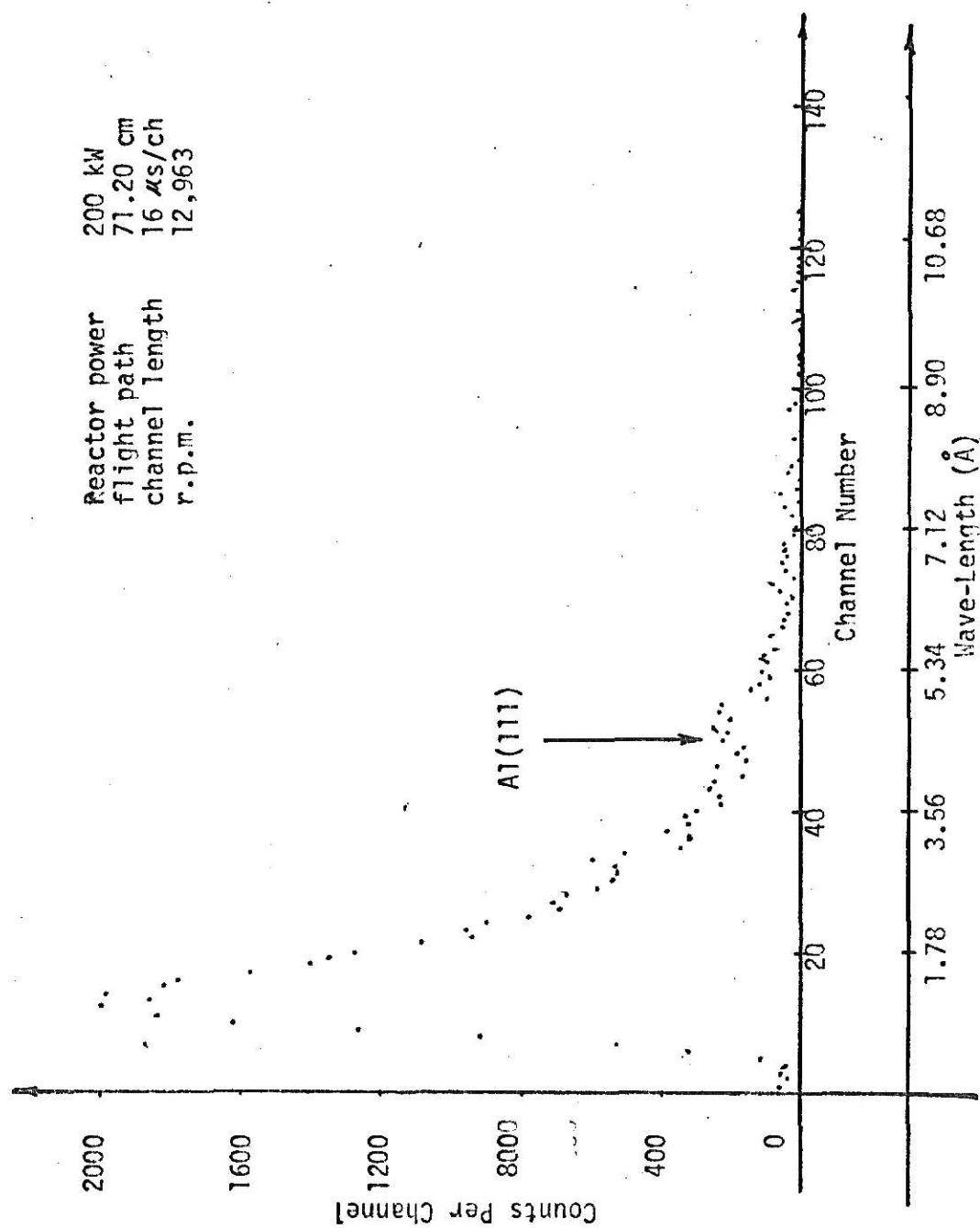


Fig. 22 Time-of-flight spectrum after correction

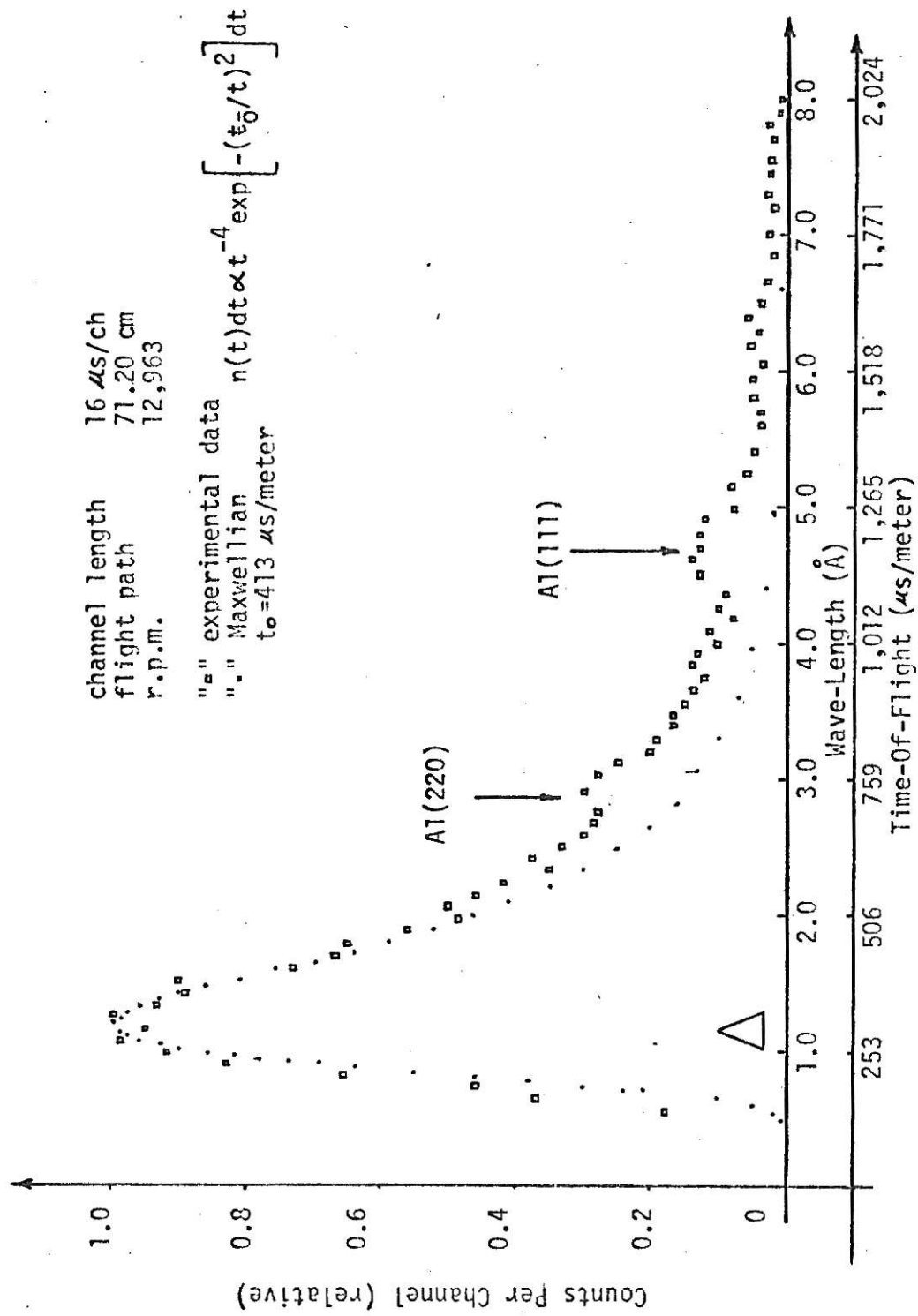


Fig. 23 Neutron spectrum after correction

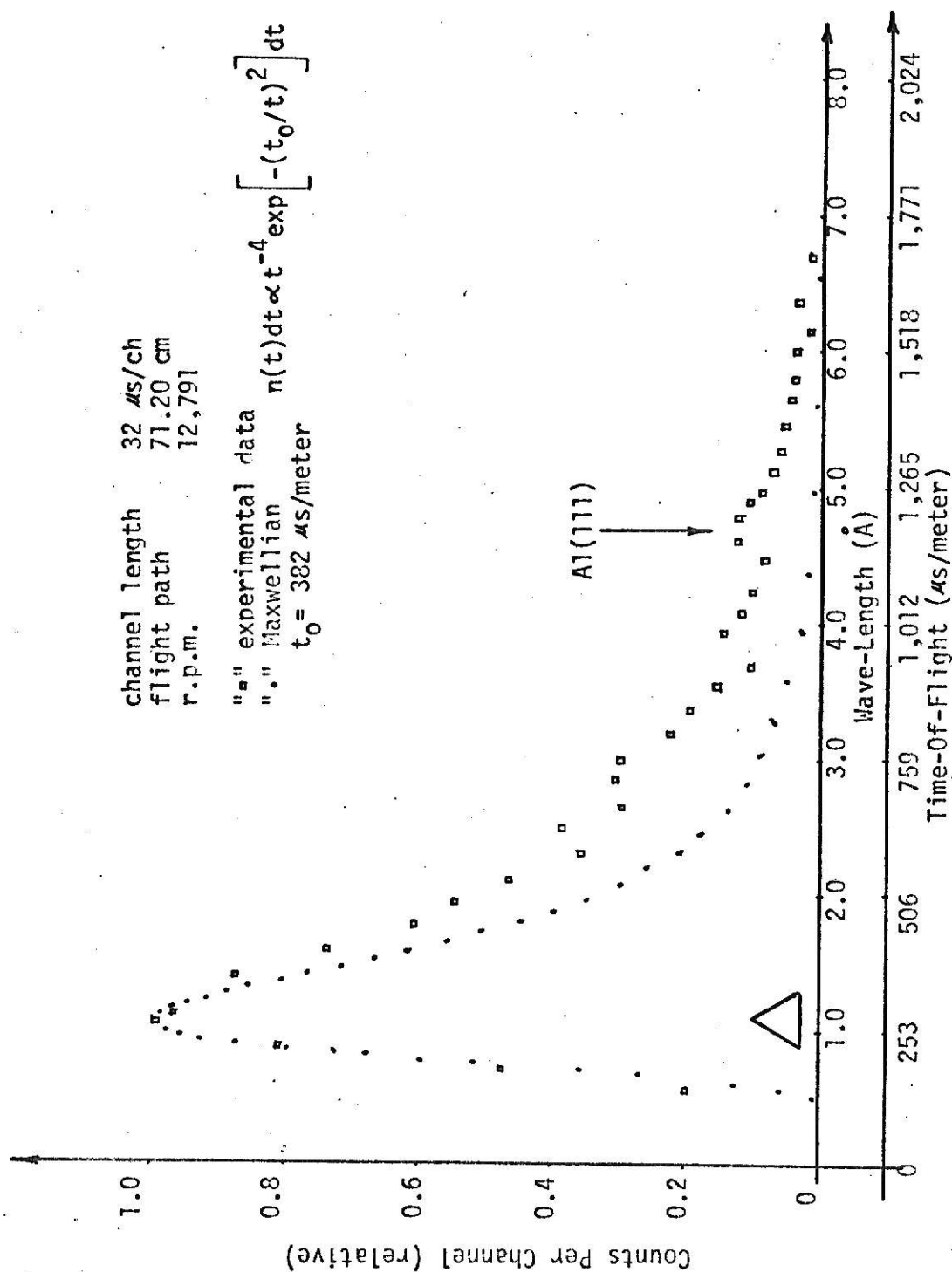


Fig. 24 Neutron spectrum after correction

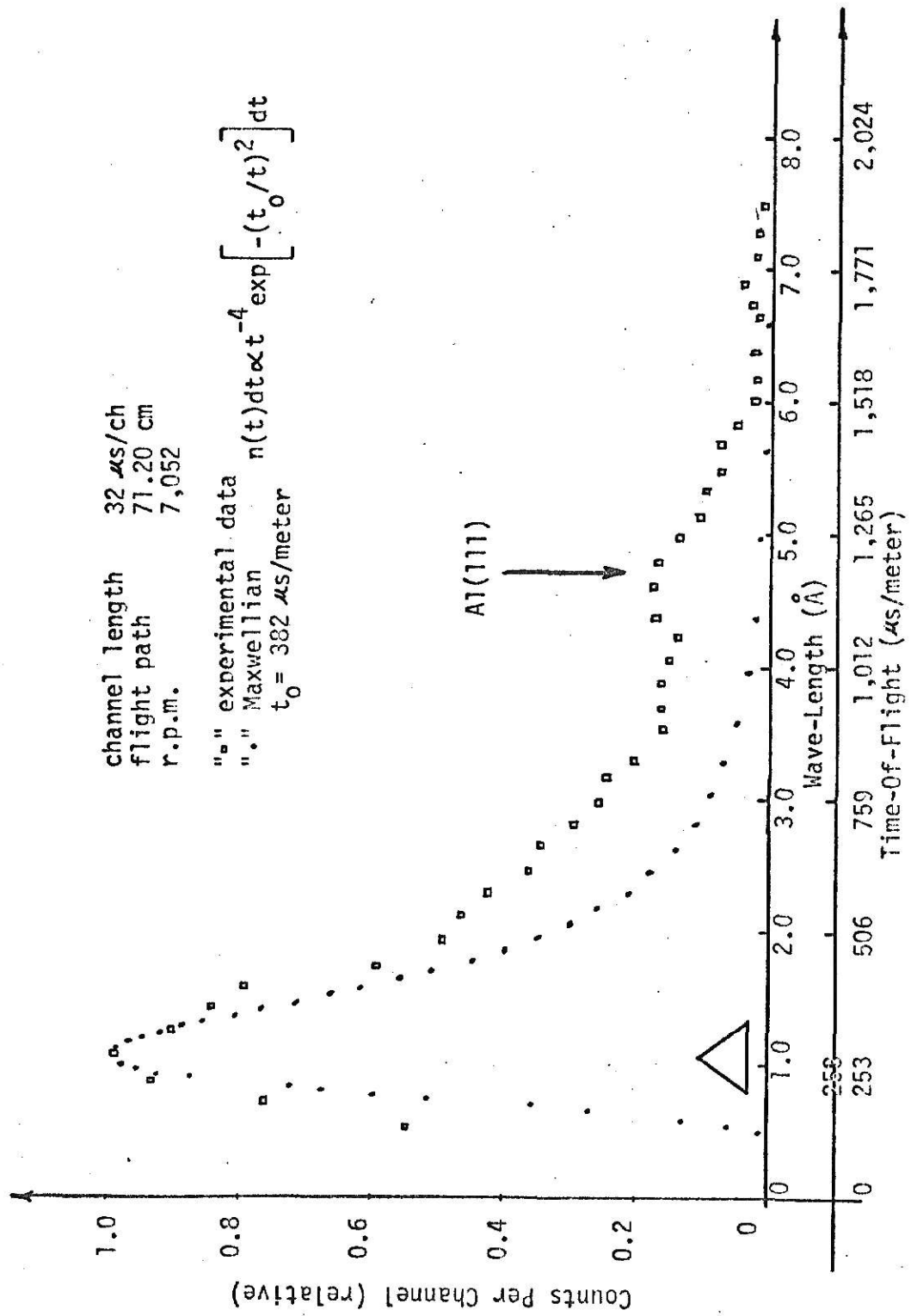


Fig. 25 Neutron spectrum after correction

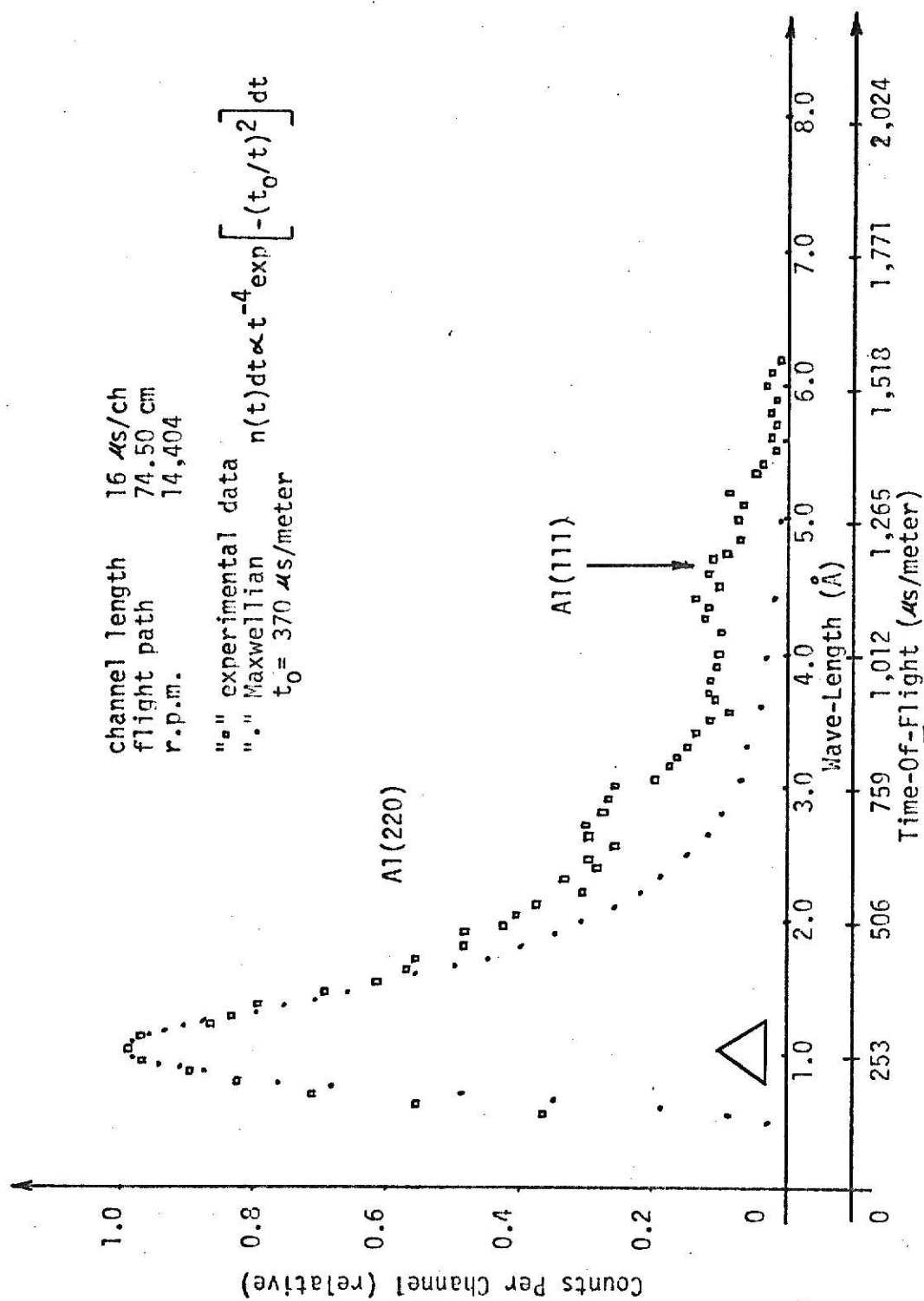


Fig. 26 Neutron spectrum after correction

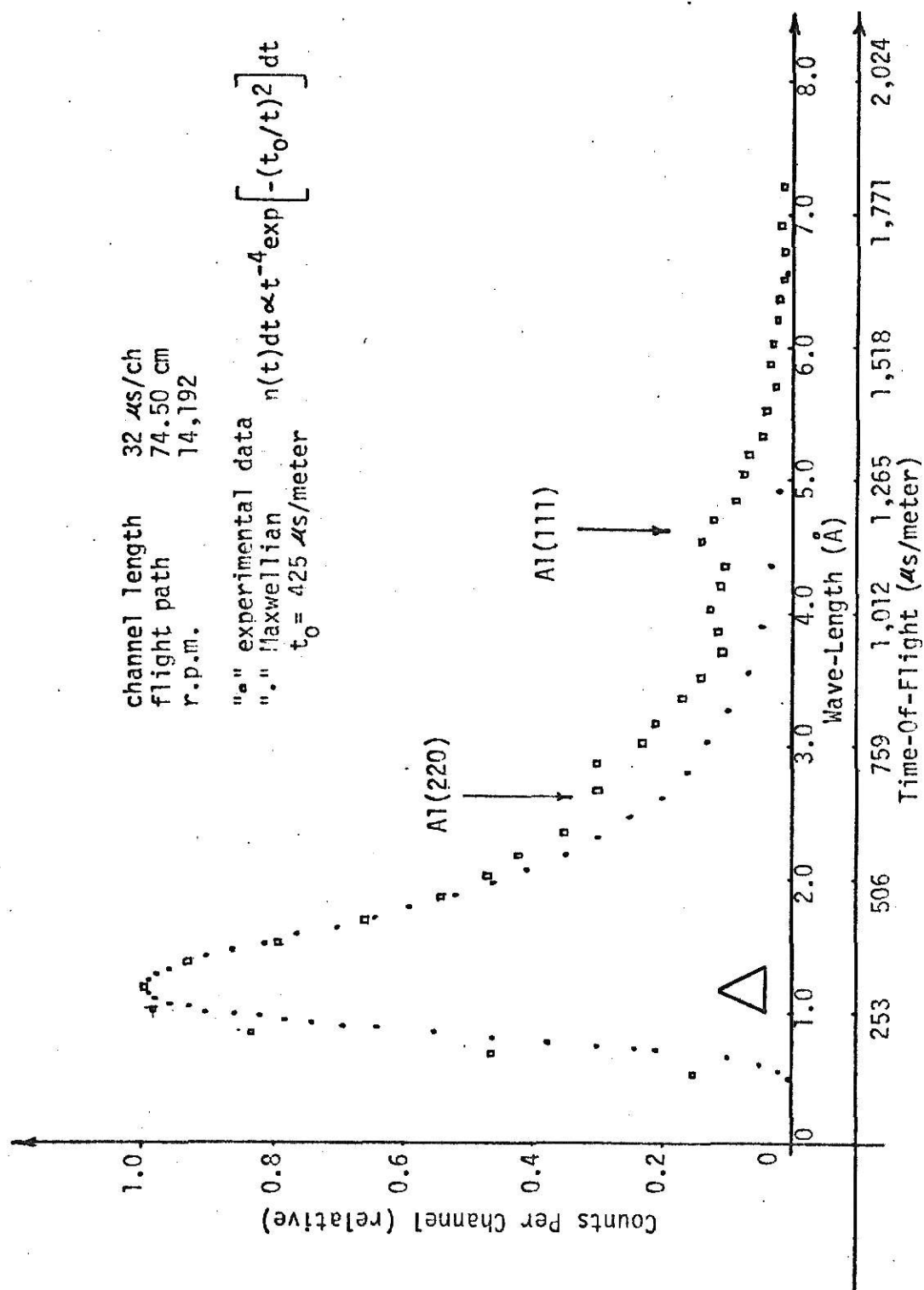


Fig. 27 Neutron spectrum after correction

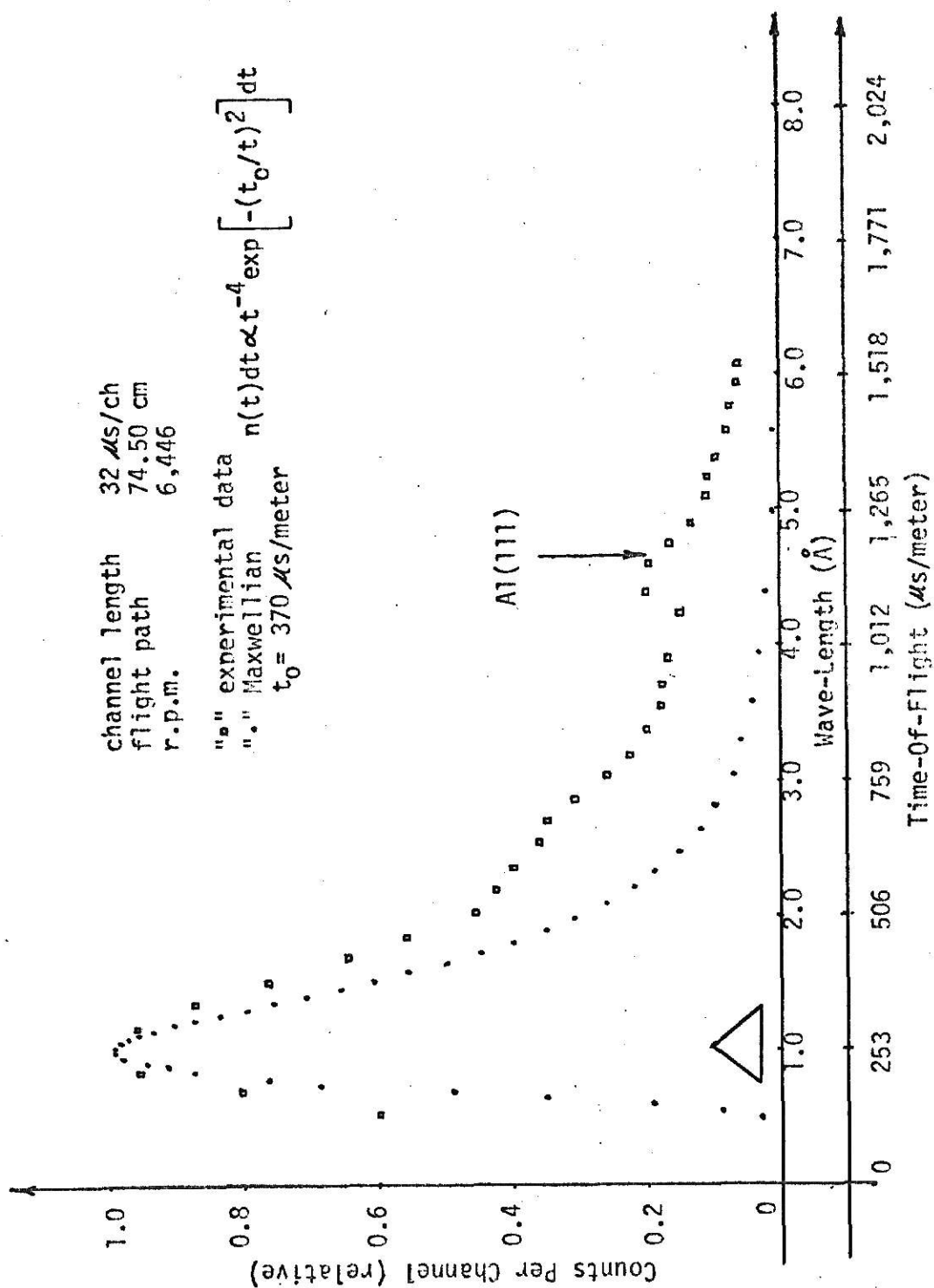


Fig. 28. Neutron spectrum after correction

another method. A method described by Larsson et al., ⁽¹⁹⁾ is adopted in this work in order to obtain the experimental points of the rotor transmission. The experimental points were determined by operating the rotor at different rotor angular velocities ω and recording the intensity attenuation of the counting rate for a selected neutron velocity. The greatest transmission was considered as a normalization factor. Then, the experimental points were obtained from a computation of $x = R \sqrt{\frac{\omega}{dv}}$. The comparison of calculated $J(x)$ and experimental $J(x)$ are shown on Table I and Fig. 4.

Table I. Comparison of Experimental and Calculated Slit Transmission

ω (rad/sec)	v (m/s)	$x = R \sqrt{\frac{\omega}{dv}}$	Rotor Transmission $J(x)$	
			Calculated	Experimental
1358	1203	0.521	0.81	0.83
1570	1203	0.550	0.76	0.70
1487	1203	0.546	0.77	0.84

The slit width d for calculation of x is taken to be the actual thickness of the window material, $d=0.08126$ centimeter under ideal parallel neutron beam. This is justifiable because the shape of the opening angle of the rotor agrees very well with the theoretical shape (triangular shape, see Fig. 18). Thus the possible divergency of the neutron beam is considered negligible. The experimental results obtained by varying ω instead of neutron velocity, v are not expected to be very precise, but nevertheless rather good agreement with the expected values were obtained.

6.4 System Resolution

In order to check the experimental electronics zero-time calibration and the system time resolution, usually some measurements of slow neutron coherent scattering should be performed. This type of scattering occurs in many polycrystalline materials such as Be, Fe, Al, Mg, and Bi, etc. Since when a thermal neutron spectrum passes through the polycrystalline materials, the neutron transmission is governed by the Bragg equation

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

The maximum neutron wavelength, λ_m , occurs for neutron motion perpendicular to the crystal planes and has a value

$$\lambda_m = 2d'_m$$

where d'_m is the maximum spacing of crystal planes at which the neutrons cross. Only neutrons with wavelength shorter than $2d'_m$ undergo coherent scattering, thus a sharp scattering cross-section break at cut-off wavelength appears. Such a sharp break will be rounded off by the resolution of the chopper if the beam is analyzed by the chopper. Karsson and Otnes⁽²⁰⁾ suggested a method of defining the resolution of the neutron spectrometer in their paper. It states that the Bragg cut-off is defined by the inflection point of the observed spectrum and the projection on the time-of-flight axis of the tangent at the point of inflection defines the width of the resolution function (Fig.

30). In this work a prominent break constantly appears at a wave length corresponding to scattering from the $\text{Al}(111)^{(21)}$ plane in the time-of-flight spectrum measurements. Thus to a certain extent, the determination of the resolution of the system becomes possible. From Fig. 29 and Fig. 30, the experimental resolution and calculated resolution were obtained and are given in Table II for comparison.

Table II. Comparison of Observed and Calculated Resolutions

Observed Resolution	Calculated Resolution
76.4 (μs)	24.6 (μs)

The above table was obtained from data obtained by putting an aluminum block 9.5 cm in length, in the transmitted beam as shown in Fig. 29 and Fig. 30.

From the $\text{Al}(111)$ break point, the previous electronics zero-time adjustment was checked by observing the $\text{Al}(111)$ peak location on the time-of-flight axis. The following table was obtained.

Table III. Comparison of Observed and Calculated Bragg Cut-Off

Inflection Point		Error (μs)
Observed	Calculated	
784 (μs)	838 (μs)	838-784=54
$\overset{0}{4.35}$ ($\text{\AA}$)	$\overset{0}{4.67}$ ($\text{\AA}$)	

It is noted that the electronics zero-time adjustment falls behind the ideal zero-time by 54 microseconds.

6.5 Discussion of the Results

The experimental neutron spectra (Fig. 23 to Fig. 28) obtained with the chopper effectively demonstrate that the objectives of the research were

very adequately met. The design, fabrication and operation of the chopper system was successful. The neutron spectra obtained from the tangential beam port contain enough detail that the coherent scattering from the aluminum filter (see Fig. 29) is discernible. In fact, the detail obtained was sufficient so that this feature could be used to determine the system resolution (Fig. 30).

From the measured neutron spectra (Fig. 23 to Fig. 28), it is noted that the shorter wavelength region agrees well with the theoretical Maxwellian distribution and the longer wavelength region is slightly higher than the theoretical distribution. Since longer wavelength neutrons undergo coherent scattering when they pass through the graphite, bismuth, and aluminum media, thus it is expected that a higher counting rate than predicted by theory will result. The observed neutron spectra obtained in this work are in agreement with Egelstaff's⁽²²⁾ results.

The most probable time-of-flight, t_0 , was found with values in the range from 370 $\mu\text{s}/\text{m}$ to 425 $\mu\text{s}/\text{m}$. This is due to the errors of electronics zero-time resulting from the observation of the oscilloscope screen at different channel lengths and different chopper rotation speeds. The longer channel length especially provides the bigger time error. Also another time error introduced arises from the unstable operation of the pulse generator (section 4.2.7). With consideration of the above timing-errors possible during the measurements, the best estimate of the most probable neutron velocity is $2,420 \pm 260$ m/s which corresponds to a neutron temperature of 359 ± 88 K⁰.

The observed resolution is three times larger than the calculated resolution. The reason for this result is that the calculated resolution is only considered as a function of two parameters, i.e., neutron burst duration time,

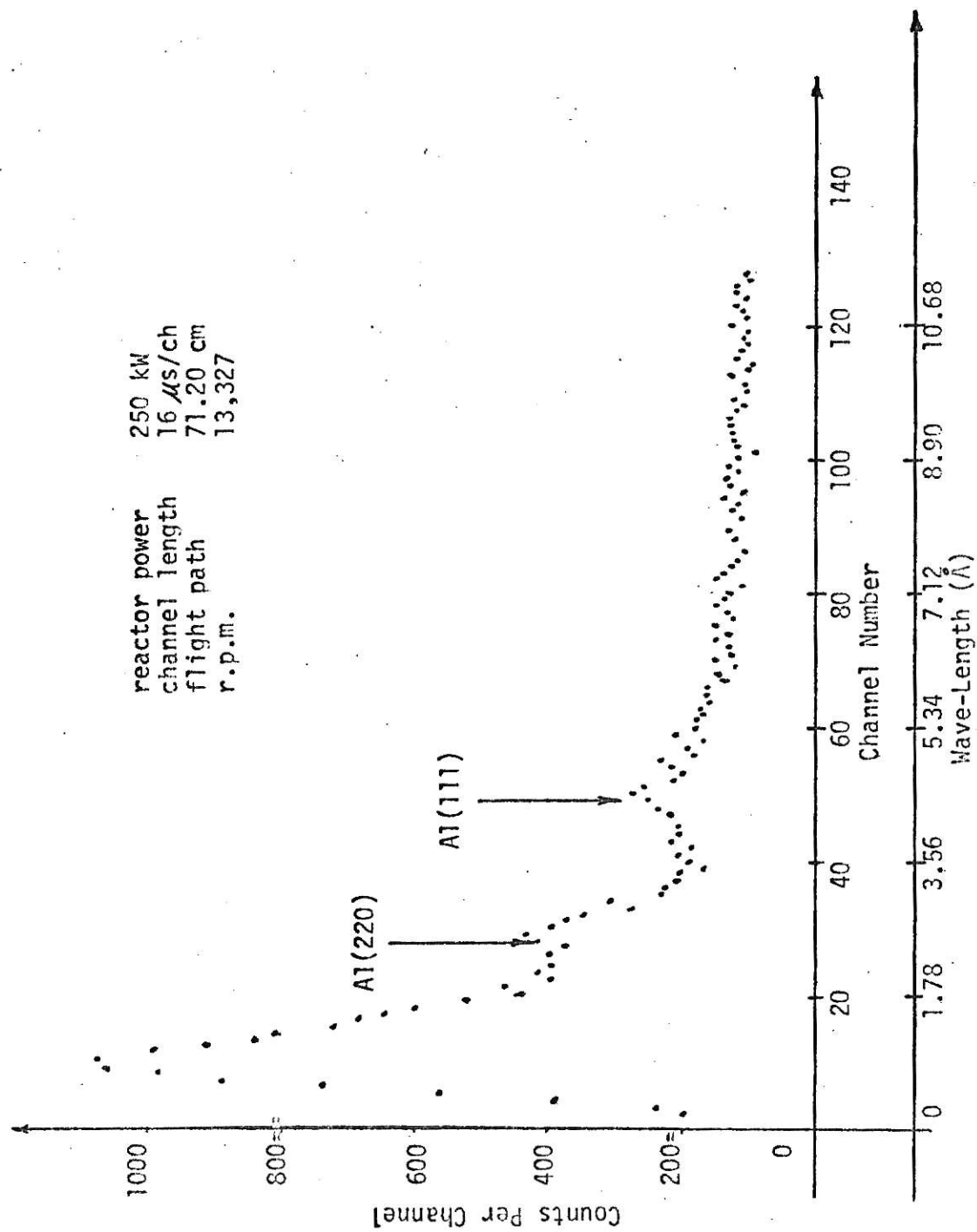


Fig. 29 Time-of-flight spectrum filtered by 9.5 cm aluminum

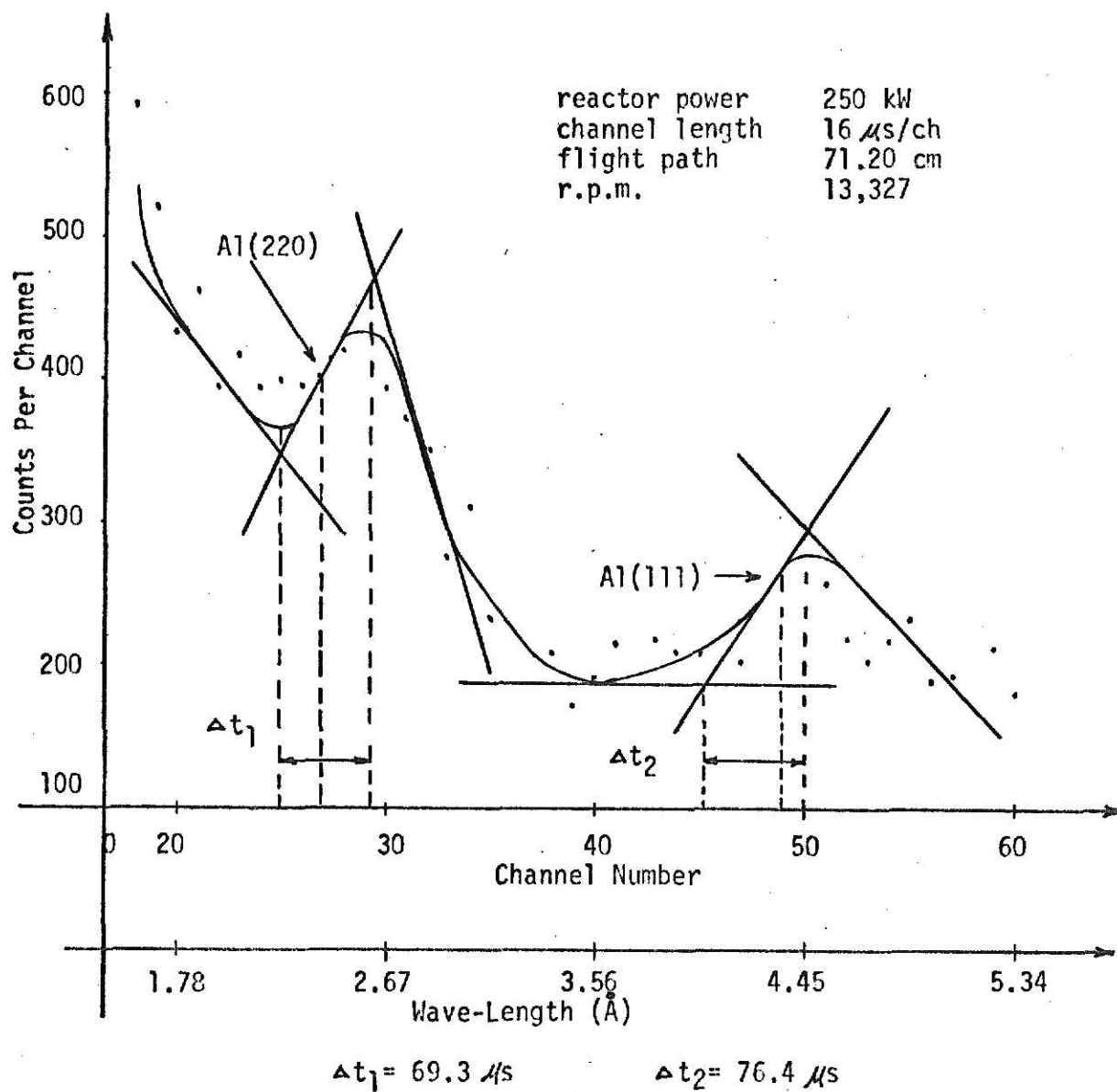


Fig. 30 Calibration of electronics zero-time and experimental determination of system resolution

T_n , and the channel length, τ (see equation (35)). In addition, for the measurements, the maximum flight path available in this work, 76.0 cm is affected by the zero-time error and beam divergency. Therefore, the observed resolution is larger than the calculated resolution as expected.

The experimental conditions for the best system resolution were found to be

- a. high rotation speed
- b. short channel length, and
- c. maximum flight path

The above three conditions are verified by comparing Fig. 23 with Fig. 25 and Fig. 27 to Fig. 28.

The above obtained results have shown that the neutron time-of-flight spectrometer constructed for the KSU Triga Mark II reactor is able to be used for measuring the thermal neutron spectrum with very good accuracy. It will also be suitable for use by undergraduate students at the senior level for measuring the thermal neutron spectrum and for learning about time-of-flight spectrometer techniques.

7.0 SUGGESTIONS FOR FURTHER STUDY

Additional work can be performed in order to improve the over-all system resolution. Also a complete investigation of the effectiveness of the whole system should be carried out. These additional refinements can be done by reducing the slit width d , or increasing the radius of rotor, in order to obtain longer flight path lengths and by measuring total cross-sections of some $1/v$ materials such as Au, In, and Li.

A low efficiency neutron detector, BF_3 , which is suitable for general purpose measurements of neutrons was used in this work. It is suggested that a higher efficiency neutron detector be used in order to be able to perform the total neutron transmission of some $1/v$ materials. It would also be more convenient if a new model of the TMC multi-channel analyzer (model 440) would be available. This would greatly simplify the graph plotting and data correction by using X-Y plotter and magnetic tape data output.

8.0 ACKNOWLEDGEMENTS

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10.0 APPENDICES

10.1 APPENDIX A: The Chopper Assembly

One of the important objectives in this investigation was the construction of the neutron chopper. The schematic diagrams of the component parts of the neutron chopper are presented here in Fig. 31 to Fig. 33. Photographs of the completed assembly were presented earlier (Fig. 8 and Fig. 12).

Fig. 31 The Chopper assembly I

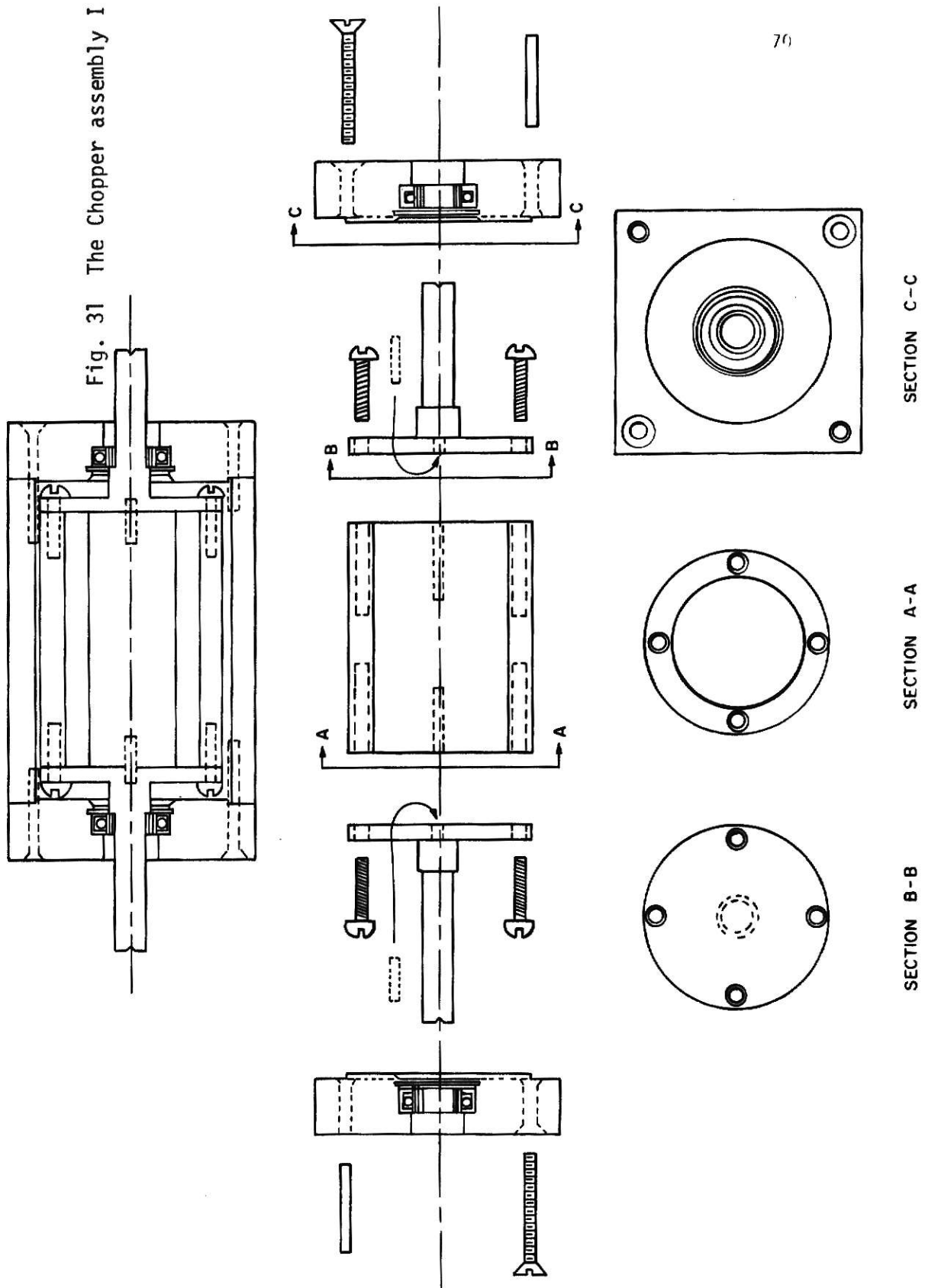
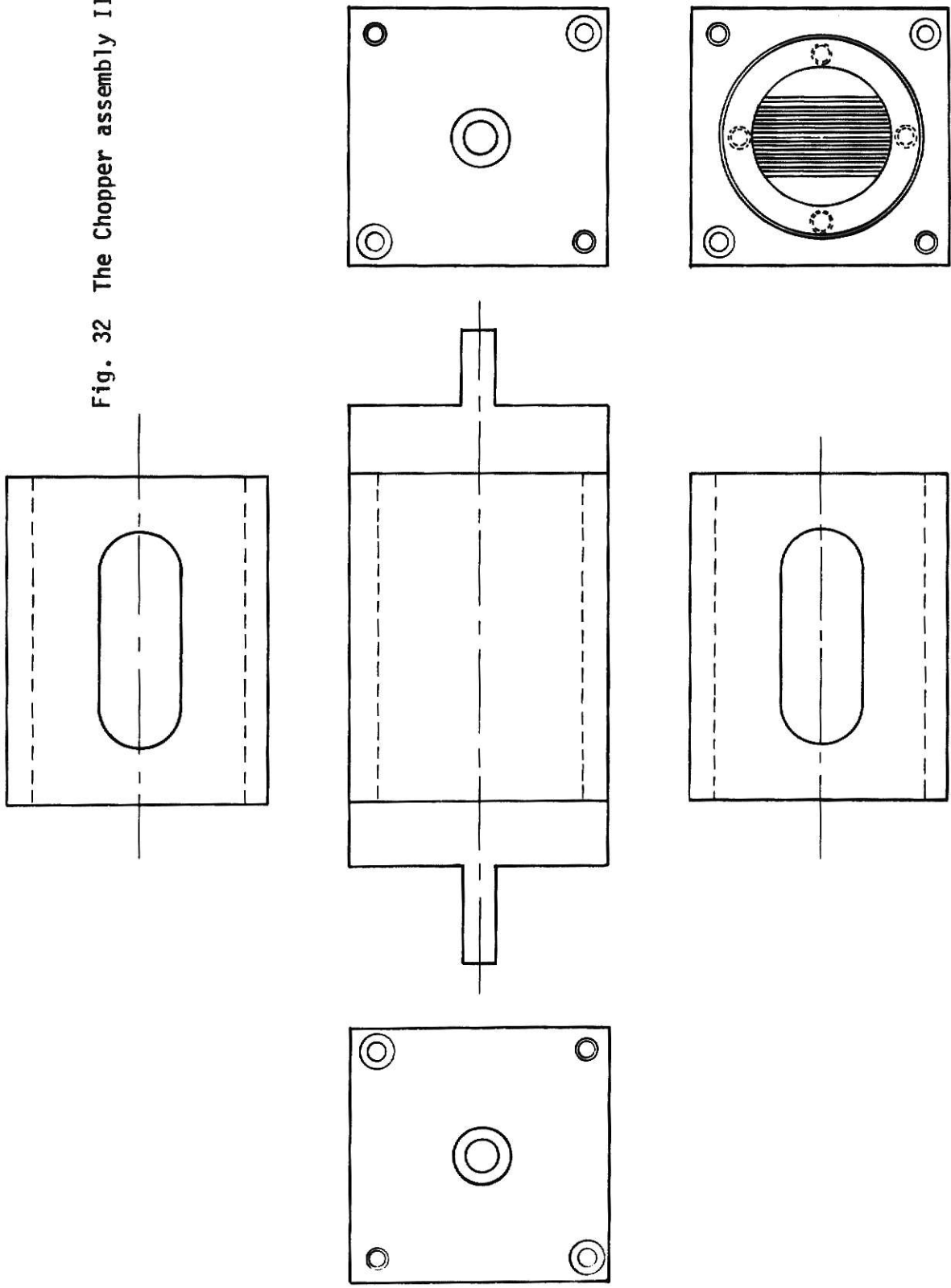


Fig. 32 The Chopper assembly II



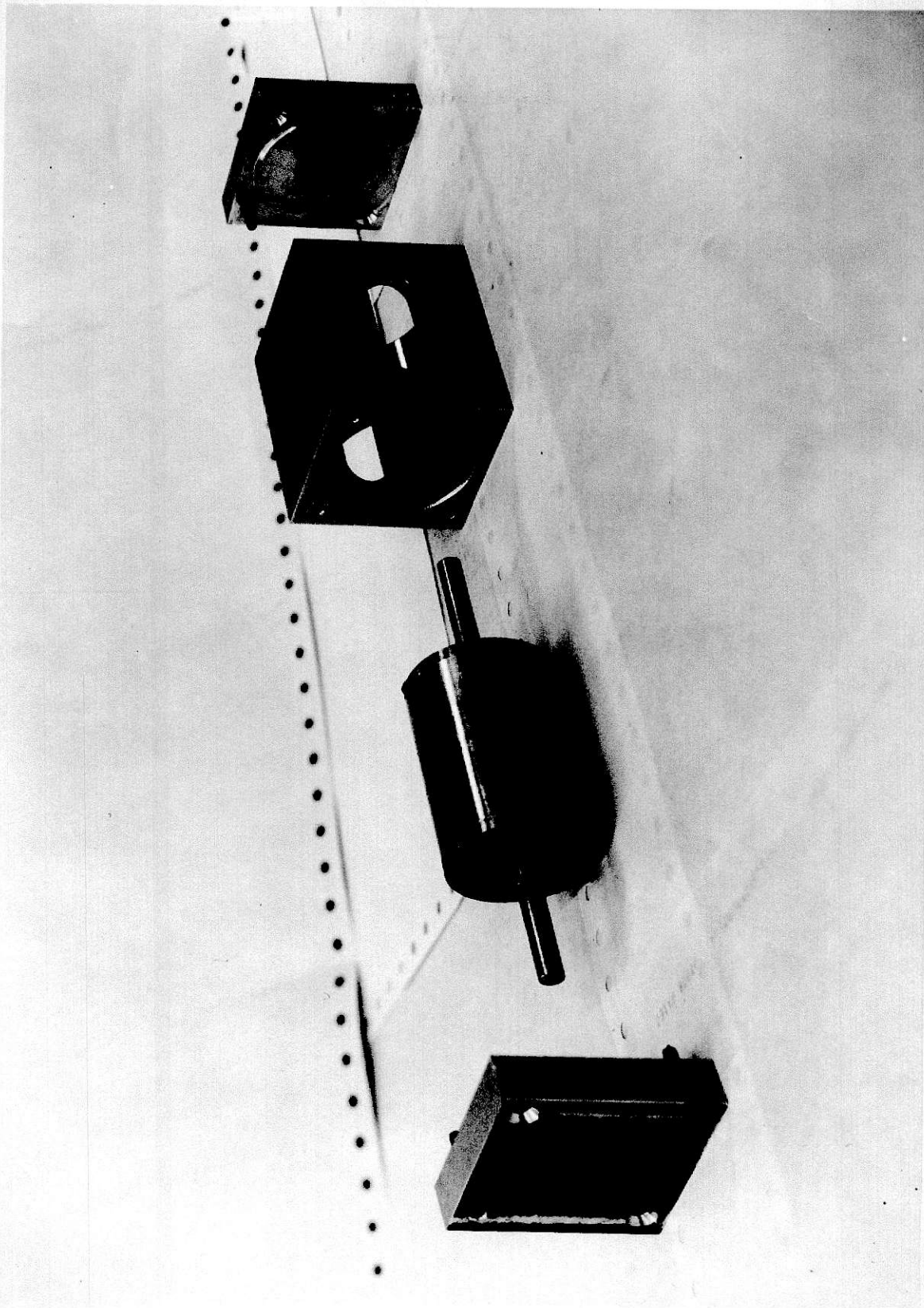


Fig. 33 The chopper assembly III

10.2 APPENDIX B: Derivation of Equations (26) and (27)

Due to the symmetry of the $f(v, t_0)$ functions, the area under the shape of the neutron burst may be represented as

$$\text{Area} = 2J(v) = 2 \int_{t_0} f(v, t_0) dt_0$$

Case 1. $\frac{4\omega R}{d} \leq v < \infty$ range

From Equation (21)

$$2J(v) = 2 \int_0^{\frac{2R}{v}} \left[1 - \frac{\omega v}{4d} \left(\frac{2R}{v} + t_0 \right)^2 \right] dt_0 + 2 \int_{\frac{2R}{v}}^{\frac{d}{2\omega R}} \left(1 - \frac{2\omega R}{d} t_0 \right) dt_0$$

The evaluation of the first term on the right-hand side;

$$\begin{aligned} \int_0^{\frac{2R}{v}} dt_0 - \frac{\omega v}{4d} \int_{\frac{2R}{v}}^{\frac{4R}{v}} \left(\frac{2R}{v} + t_0 \right)^2 d \left(\frac{2R}{v} + t_0 \right) &= \frac{2R}{v} - \frac{\omega v}{4d} \cdot \frac{1}{3} \cdot \left[\left(\frac{2R}{v} + t_0 \right)^3 \right]_{\frac{2R}{v}}^{\frac{4R}{v}} \\ &= \frac{2R}{v} - \frac{\omega v}{12d} \left[\left(\frac{4R}{v} \right)^3 - \left(\frac{2R}{v} \right)^3 \right] = \frac{2R}{v} - \frac{\omega v}{12d} \cdot \left(\frac{2R}{v} \right)^3 \cdot (2^3 - 1) \\ &= \frac{2R}{v} - \frac{14\omega R^3}{3dv^2} \end{aligned}$$

The evaluation of the second term on the right-hand side;

$$\int_{\frac{2R}{v}}^{\frac{d}{2\omega R}} \left(1 - \frac{2\omega R}{d} t_0 \right) dt_0 = \frac{-d}{2\omega R} \int_{1-\frac{4\omega R}{dv}}^0 \left(1 - \frac{2\omega R}{d} t_0 \right) d \left(1 - \frac{2\omega R}{d} t_0 \right) =$$

$$\begin{aligned}
&= -\frac{d}{2\omega R} \cdot \frac{1}{2} \cdot \left[\left(1 - \frac{2\omega R}{d} t_0\right)^2 \right]_{1 - \frac{4\omega R^2}{dv}}^0 \\
&= \frac{d}{4\omega R} \cdot \left(1 - \frac{4\omega R^2}{dv}\right)^2 = \\
&= \frac{d}{4\omega R} - \frac{2R}{v} + \frac{4\omega R^3}{dv^2}
\end{aligned}$$

Thus

$$\text{Area} = 2J(v) = \frac{d}{2\omega R} \left(1 - \frac{8}{3} \frac{\omega^2 R^4}{d^2 v^2}\right) \quad (26)$$

Case 2. $\frac{4\omega R}{d} \geq v \geq \frac{\omega R^2}{d}$ range

$$\begin{aligned}
\text{Area} = 2J(v) &= 2 \int_{t_0}^{2\sqrt{\frac{d}{\omega v}} - \frac{2R}{v}} f(v, t_0) dt_0 = 2 \int_0^{2\sqrt{\frac{d}{\omega v}} - \frac{2R}{v}} \left[1 - \frac{\omega v}{4d} \left(\frac{2R}{v} + t_0\right)^2 \right] dt_0 \\
&= 2 \left(\int_0^{2\sqrt{\frac{d}{\omega v}} - \frac{2R}{v}} dt_0 - \frac{\omega v}{4d} \int_{\frac{2R}{v}}^{2\sqrt{\frac{d}{\omega v}}} \left(\frac{2R}{v} + t_0\right)^2 d\left(\frac{2R}{v} + t_0\right) \right) = \\
&= 2 \left(\left(2\sqrt{\frac{d}{\omega v}} - \frac{2R}{v}\right) - \frac{\omega v}{12d} \left[\left(2\sqrt{\frac{d}{\omega v}}\right)^3 - \left(\frac{2R}{v}\right)^3 \right] \right) = \\
&= 2 \left(\left(2\sqrt{\frac{d}{\omega v}} - \frac{2R}{v}\right) \cdot \left[1 - \frac{\omega v}{12d} \cdot \left(\frac{4d}{\omega v} + \frac{4d^{\frac{1}{2}} R}{\omega^{\frac{1}{2}} v^{\frac{3}{2}}} + \frac{4R^2}{v^2}\right) \right] \right) = \\
&= \frac{d}{\omega R} \left(\frac{4\omega^2 R^4}{3d^2 v^2} - \frac{4\omega R^2}{dv} + \frac{8\omega R}{3d} \sqrt{\frac{d}{\omega v}} \right) \quad (27)
\end{aligned}$$

THE DESIGN, CONSTRUCTION AND OPERATION
OF A SLOW NEUTRON CHOPPER

by

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AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

The main purpose of the investigation was to design, construct and operate a slow neutron chopper for use with the KSU Triga Mark II reactor. This report presents the details of the design and construction of the neutron chopper and the associated electronics instrumentation that is necessary for utilization of the chopper. Initial chopper mechanical balance as well as the electronics zero-time adjustment were tested and determined. Neutron spectra for different channel lengths and rotation speeds were measured for two different flight paths. Also a Bragg-cut-off experiment was performed in order to determine the over-all system resolution. A comprehensive slow neutron chopper theory is included in this work so that the experimental results can be accurately interpreted.

It is shown that the thermal neutron spectrum at the tangential beam port is nearly Maxwellian with an effective temperature of $359 \pm 88 \text{ K}^{\circ}$. The experimental spectra deviate from the Maxwellian spectrum in the lower velocity range. This deviation is attributed to coherent scattering in the collimator and chopper rotor window material.