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RESUMO

Um seletor mecânico de velocidades, construído no Instituto de Energia Atômica (IEA), foi instalado em frente a um canal de irradiação tangencial, do reator tipo piscina do IEA.

O rotor do seletor de velocidades tem a forma de um cilindro com canais helicoidais em sua periferia; em conseqüência, a energia dos neutrons é determinada pela velocidade angular do rotor.

Êsse instrumento pode ser usado como um monocromador de baixa resolução ou como um filtro, quando acoplado a um espectrômetro de cristal, destinado a eliminar neutrons provenientes de reflexões de ordens superiores.

Devido as dimensões finitas do canal, o espectro de saída do seletor não é monocromático. Foi estabelecida a relação teórica entre o comprimento de onda médio do espectro de neutrons emergentes do seletor e o comprimento de onda no caso de um seletor ideal, e foi determinada também a função de transmissão do seletor.

As determinações experimentais dessa relação entre os comprimentos de onda do espectro emergente do seletor, para várias velocidades de rotação, foram feitas com um expectrômetro de cristal.

A secção de choque do ouro é apresentada mostrando o funcionamento do seletor como filtro quando acoplado ao espectrômetro de cristal.

SOMMAIRE

Un sélecteur mechanique de vitesses a été construit à l'Instituto de Energia Atômica (IEA) pour la sélection de neutrons lents, en utilisant des canaux helicoidaux tournants. Il a été placé en face d'un canal d'irradiation tangentiel de la pile piscine de l'IEA.

Cet appareil peut être utilisé comme un monochromateur de baisse résolution ou comme un filtre pour les neutrons dûs aux reflexions d'ordre supérieur dans un cristal.

La fonction de transmission a été determinée parce que le spectre transmis n'est pas monocromatique à cause des dimensions finies du canal. Le rapport entre la longueur d'onde moyenne transmise et la longueur d'onde dans le cas idéal a été établi. La détermination experiméntal de ce rapport a été faite avec un spéctrométre à cristal par moyen de l'analyse du faisceau sortant du selecteur. On presente la section efficace de l'or pour montrer le fonctionnement du sélecteur comme filtre, quand il est assemblé au spectrométre à cristal.

ABSTRACT

A mechanical velocity selector (MVS) with helical channels , for the monochromatization of slow neutrons, has been built at the Instituto de Energia Atômica (IEA). The selector was installed at a tangential beam hole in the swimming pool reactor of the IEA. The channel rotation velocity determines the emergent neutron energy. This instrument is used as a low resolution monochromator and as a filter for higher order neutrons reflected by crystals.

The finite dimensions of the channel lead to a non mono-chromatic transmitted spectrum. The average wavelength of the MVS is compared with the ideal MVS wavelength and a relationship between them is established. The transmission function of the

selector has been determined. The experimental verification of the calculated wavelengths was made by analyzing the emergent spectrum of the selector with the crystal spectrometer. The gold cross-section measured with the neutron spectrometer coupled to the velocity selector shows its use for the elimination of the effects due to high order reflections.

INTRODUCTION

Many experiments in nuclear physics require the use of monochromatic neutron beams.

An instrument that has been less used in thermal neutron research than the single crystal spectrometer[1], is the mechanical velocity selector[2,3]. It consists usually of a number of slotted disks mounted on a common shaft, forming a solid cylinder with helical channels in the periphery. The selection of the emergent neutron energy is given by the speed of the rotor.

In the subthermal neutron energy range (i.e. below the peak of the Maxwellian distribution), a crystal spectrometer does not provide efficient energy selection because of the contribution due to reflected neutrons in second and higher orders. In order to obtain a monochromatic neutron beam in this region of energy, a MVS has been constructed at the IEA.

When the MVS is used with a crystal spectrometer, it filters out the higher order neutrons. The selector may be used alone if only a monochromatic beam of low resolution is required.

For a given rotational speed, the resolution of this instrument is determined by the inclination of the channel and by the angular divergence of the incident beam.

The maximum speed of the selector and the neutron back-ground determine the range of energy for a given inclination of the helical channel.

THEORETICAL CONSIDERATIONS

Consider a cylinder of length L and radius R_o, with a narrow helical channel along its surface so as to progress to an angle ϕ_o in the cylinder length (figure 1). Let us suppose this cylinder to be made of a material opaque to neutrons, and rotating about its axis with a constant angular velocity, and a polychromatic neutron beam entering the channel.

Only neutrons with velocity V_n, as determined by the velocity selector parameters will leave the channel.

The wavelength associated with the neutron is

$$\lambda = \frac{h}{m\ V_n}$$

where m is the mass of the neutron and h is Planck's constant.

A neutron travelling parallel to the cylinder axis will be able to emerge from the channel mantaining a constant distance from the walls, only if its velocity V_n satisfies the following condition:

$$\frac{L}{V_n} = \frac{\phi_o}{W}$$

or

$$\lambda_o = \frac{h\ \phi_o}{m\ L\ W} \qquad (1)$$

Hence

$$\lambda_o = \frac{h}{2\pi m L R_o} \quad \frac{S}{f}$$

where f is the rotation frequency, and S is the arc measured on the surface given by the expression $S = R_o \varnothing_o$.

TRANSMISSION FUNCTION

Let us call $F_o(\lambda)$ the spectral distribution of the incident neutron beam on the selector and $F(\lambda)$ the spectral distribution of the selector emergent beam.

Following the notation of Dash and Sommers[2] we write

$$F(\lambda) = T(\lambda) \; F_o(\lambda)$$

where $T(\lambda)$ is called "Transmission function".

The determination of $T(\lambda)$ is made by calculating the neutron probability to traverse the channel. For this calculation we use two systems of coordinates : the laboratory system in which the neutron moves uniformly along a straight line and the system rigidly connected with the velocity selector, which moves with an angular velocity W in relation to the laboratory system.

Then a parallel beam will leave the channel only if it has, in the rotor system of coordinates, a divergence smaller than or equal to the maximum channel divergence Θ (figure 2).

The neutron velocity $\vec{V}$ in the rotor system will be

$$\vec{V} = \vec{V}_n - \vec{V}_s$$

where $\vec{V}_n$ is the neutron velocity and $\vec{V}_s$ is the tangential velocity of a rotor surface point, both in the laboratory system.

The probability of the neutron to enter one of the N channels is

$$T_o = \frac{N \Psi}{2 \pi}$$

The probability neutrons leaving the channel depends on the angle β as determined by the velocity $\vec{V}$ and the walls.

We shall analyze what happens when β assumes the boundary values.

1) $/\beta/ > \theta$

In this case, the probability of a neutron leaving the channel is zero, because it will reach the channel walls.

2) $/\beta/ =$ zero

In this case, the neutron traverses the channel at a constant distance from the walls; hence the neutron has the wavelength λ_o and its probability of leaving the channel is unity. Thus the probability of leaving the channel is T_o.

3) $/\beta/ < \theta$

case a) Parallel incident neutron beam wavelength λ between $\lambda_o - \Delta\lambda < \lambda < \lambda_o + \Delta\lambda$
The neutron path inside the channel forms an angle with the wall. As the neutron traverses the channel, it will get closer to the channel wall than when it entered it and its exit slot will be reduced by $R\Delta\phi\,(\lambda)$, with $\Delta\phi$ between

$$-\frac{\Psi}{2} < \Delta\phi < \frac{\Psi}{2}$$

case b) Divergent beam, with wavelength λ_o.

In this case, the beam has a small angular spread of $2\alpha_o$. The magnitude of α_o is given by the collimating system dimensions or by the detector dimensions. Also these neutrons will have their exit slot reduced by $R\,\Delta\phi_1(\alpha)$ where $-\frac{\Psi}{2} < \Delta\phi_1 < \frac{\Psi}{2}$

Let us consider now the cases a and b, i.e. neutrons with wavelength λ between $\lambda_o - \Delta\lambda < \lambda < \lambda_o + \Delta\lambda$ and angular divergence α between $-\alpha_o < \alpha < \alpha_o$

Neutrons in these conditions will have their exit slot reduced by $R\,\Delta\phi(\lambda) + R\Delta\phi_1(\alpha)$.

The probability of this neutron not leaving the channel is:

$$\frac{|\Delta\phi(\lambda) + \Delta\phi_1(\alpha)|}{\Psi}$$

and the probability of leaving the channel is

$$\left(1 - \frac{|\Delta\phi(\lambda) + \Delta\phi_1(\alpha)|}{\Psi}\right)$$

As the probability of the neutron entering the slots is T_o, the transmission function will be

$$T(\lambda,\alpha) = T_o\left(1 - \frac{|\Delta\phi(\lambda) + \Delta\phi_1(\alpha)|}{\Psi}\right)$$

The beam angular divergence $2\alpha_o$ has the effect of modifying the effective rotor length by a factor sec α_o. If we suppose α_o very small we can neglect all effects involving second order terms in α_o. We have : $\Delta\phi_1(\alpha) = \frac{L\alpha}{R}$

From (1) we have : $\Delta\phi(\lambda) = \frac{\Delta\lambda}{K}$, where $K = \frac{h}{m\,L\,W}$

So, $$T(\lambda,\alpha) = T_o\left(1 - \left|\frac{\lambda - \lambda_o}{\Lambda} + \frac{L\alpha}{R\,\Psi}\right|\right)$$

Where Λ is defined by $\Lambda = K\Psi$

If we neglect the dependance on R, setting $R = \bar{R}$, and supposing a constant neutron distribution in relation to the tangential angle, we may write

$$T(\lambda) = \frac{\int_{-\alpha_o}^{+\alpha_o} T(\lambda,\alpha)\, d\alpha}{\int_{-\alpha_o}^{+\alpha_o} d\alpha}$$

with this assumption the transmission function may be written as:

$$T(\lambda) = T_o\, h(\lambda - \lambda_o),$$

where

$$h(\lambda - \lambda_o) = \frac{1}{2\alpha_o}\int_{-\alpha_o}^{\alpha_o}\left(1 - \left|\frac{\lambda - \lambda_o}{\Lambda} + \frac{L\alpha}{\bar{R}\,\Psi}\right|\right) d\alpha$$

We define now a parameter

$$P = \frac{L\alpha_o}{\bar{R}\,\Psi}$$

that depends on the selector geometrial characteristics and on the beam angular divergence.

The integration gives:

1) for an any value P

$$h(\lambda-\lambda_0) = \left[\frac{(\lambda-\lambda_0)}{\Lambda} + (P+1) \right]^2 \frac{1}{4P}$$

in the range

$$-(1+P) \leqslant \frac{\lambda-\lambda_0}{\Lambda} \leqslant \begin{cases} -P \\ P-1 \end{cases}$$

2) $P \geqslant 1/2$

$$h(\lambda-\lambda_0) = \frac{1}{2P} - \frac{1}{4P} \left[\frac{\lambda-\lambda_0}{\Lambda} + (P-1) \right]^2$$

in the range

$$-P \leqslant \frac{\lambda-\lambda_0}{\Lambda} \leqslant \begin{cases} 1-P \\ P-1 \end{cases}$$

3) $P \leqslant 1$

$$h(\lambda-\lambda_0) = \frac{1}{2P}$$

in the range

$$1-P \leqslant \frac{\lambda-\lambda_0}{\Lambda} \leqslant 0$$

4) $P \leqslant 1/2$

$$h(\lambda-\lambda_0) = 1 + \frac{\lambda-\lambda_0}{\Lambda}$$

in the range $P - 1 \leqslant \dfrac{\lambda - \lambda_o}{\Lambda} \leqslant - P$

5) $P \leqslant 1$

$$h\,(\lambda - \lambda_o) = 1 - \frac{P}{2} - \frac{1}{2P}\left(\frac{\lambda - \lambda_o}{\Lambda}\right)^2$$

in the range $\left.\begin{matrix} P - 1 \\ - P \end{matrix}\right\} \leqslant \dfrac{\lambda - \lambda_o}{\Lambda} \leqslant 0$

As the transmission function $T\,(\lambda)$ and the incident spectrum $F_o\,(\lambda)$ are known, we can calculate the emergent spectrum $F\,(\lambda)$, and the average wavelength $\bar{\lambda}$

We define $\bar{\lambda}$ as :

$$\bar{\lambda} = \frac{\int_{\lambda_1}^{\lambda_2} \lambda F\,(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} F\,(\lambda)\, d\lambda} .$$

where $\lambda_1 = \lambda_o - \Lambda\,(P + 1)$

and $\lambda_2 = \lambda_o + \Lambda\,(P + 1)$

In the following analysis, we compare the average wavelength $\bar{\lambda}$ to the wavelength λ_o given by the expression (1).

Using $T\,(\lambda) = T_o\, h\,(\lambda - \lambda_o)$, and making $x = \lambda - \lambda_o$ the expression becomes

$$\bar{\lambda} = \frac{\int_{-x_1}^{x_1} (x+\lambda_o)\, h(x)\, F_o(x+\lambda_o)\, dx}{\int_{-x_1}^{x_1} h(x)\, F_o(x+\lambda_o)\, dx}$$

with $x_1 = \Lambda(P+1)$. This expression gives

$$\bar{\lambda} - \lambda_o = \frac{\int_{-x_1}^{x_1} x\, h(x)\, F_o(x+\lambda_o)\, dx}{\int_{-x_1}^{x_1} h(x)\, F_o(x+\lambda_o)\, dx}$$

The signal $(\bar{\lambda} - \lambda_o)$ is given by the numerator, which , after a few transformations, can be written as

$$\int_{0}^{x_1} x\, h(x) \left[F_o(\lambda_o+x) - F_o(\lambda_o - x) \right] dx$$

The signal of the expression in brackets determines the signal of $(\bar{\lambda} - \lambda_o)$.

If $F_o(\lambda)$ is a constant, or a symetric function, we obtain

$$\bar{\lambda} = \lambda_o ;$$

If $F_o(\lambda)$ is a increasing function, it results $\bar{\lambda} > \lambda_o$ and

If $F_o(\lambda)$ is a decreasing function, $\bar{\lambda} < \lambda_o$.

RESOLUTION FIGURE OF MERIT

The emergent spectrum resolution, for a given rotation velocity, is usually defined as the ratio of the full width at half maximum to the average wavelength.

The evaluation of the selector resolution requires tedious calculation for each particular case.

We will use a simple resolution "Figure of Merit" defined by Dash and Sommers[2] as a property of the spectrometer geometry:

$$\Gamma = \frac{\Lambda \; (P+1)}{\lambda_0}$$

This expression may be written as:

$$\Gamma = \frac{\psi}{\phi_0} \qquad \frac{L\,\alpha_0}{\bar{R}\;\phi_0}$$

EXPERIMENTAL APPARATUS

The MVS was mounted in the exit of the IEA-R1 tangential beam hole. The experimental apparatus, shown in figure 4, is formed by the collimator, the mechanical velocity selector and the cristal spectrometer. (")

RESULTS

The experimental study of the MVS characteristics was undertaken with the apparatus shown in figure 4. In this experimental

(") The MVS design and construction were supervized by Dr. R.L. Zimmerman, scientist who spent one year at the IEA, on leave from the Case Institute of Technology, Cleveland, Ohio.

apparatus the beam divergence defined by the detector has the value $\alpha_o = 4.4 \; 10^{-3}$ rd, thus resulting for the selector parameter the value P = .33.

This study was made considering the most unfavourable resolution conditions. This is performed with the minimum S value, S = 2.365 cm ; for lower values we have a straight channel. The resolution figure of merit in this case is $\Gamma = .6$, i.e., 60% in wavelength.

We have determined with the crystal spectrometer the emergent spectrum for several rotation velocities; these spectra can be seen in figure 5, where they are compared to the assumed incident spectrum, a maxwellian distribution at 300° K. The experimental and theoretical resolution of these spectra are shown in Table I.

The theoretical mean wavelength ($\bar{\lambda}$ th) was calculated by numerical integration, and the experimental mean wavelength ($\bar{\lambda}$ exp) by graphical integration of the emergent spectrum. In figure 6, the curves of λ_o given by expression (1), $\bar{\lambda}_{th}$ and $\bar{\lambda}_{exp}$, can be seen and their respective values are presented in Table II, for some rotation velocities.

Cross section measurements of gold were taken with the crystal spectrometer alone, and later with this spectrometer assembled to the MVS. Thus, we have been able to verify the use of the selector as a higher order eliminator (figure 7).

Finally, we can conclude that even with the worst resolution conditions, the MVS operating in the IEAR-1, can act as a low resolution and high intensity monochromator otherwise, when assembled to the crystal spectrometer, it acts as an eliminator of higher order contamination.

ACKNOWLEDGEMENTS

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2. J.G. Dash and Sommers Jr., Rev. of Sci. Inst. 24, 91 (1953)
3. M. Ruderman and W. C. Dickinson, UCRL - 6319
4. R. Brenner and R. L. Zimmerman
Neutron velocity selector of the IEA : Mechanical Design and Electronics Control ("")

("") - Presented at the AIEA "Study Group Meeting on the Utilization of Research Reactors" - November 1963 São Paulo - Brazil

TABLE I

R P M	Theoretical resolution(%)	Experimental resolution (%)	Figure of Merit
5 000	50	48 ± 2	60
7 200	43	41 ± 2	60
9 000	44	45 ± 2	60

TABLE II

R P M	WAVELENGTH			CRYSTAL
	λ_0	$\bar{\lambda}_{Th}$	$\bar{\lambda}_{exp}$	
9 000	.96	1.03	1.05 ± .06	NaCl
7 200	1.2	1.21	1.22 ± .07	NaCl and Ca_2CO_3
6 500	1.35	1.3	1.39 ± .08	Fe_2O_3
5 000	1.73	1.57	1.59 ± .09	Ca_2CO_3
2 000	4.32	3.38	3.3 ± .20	Fe_2O_3

FIGURES INDEX

BY SEQUENCE ORDER

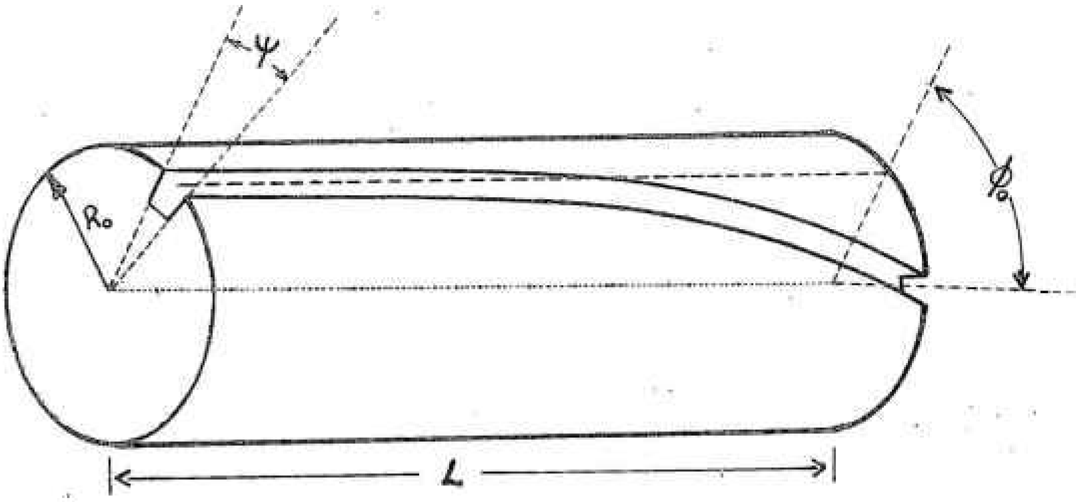


Figure 1 - Selector geometry

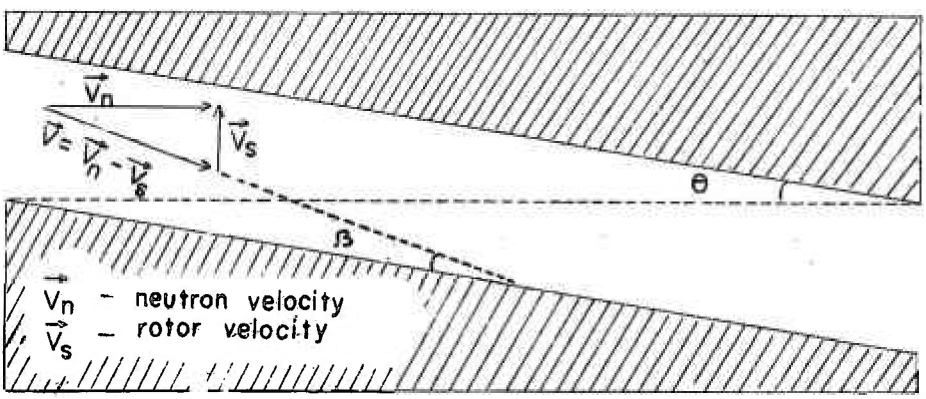


Figure 2 - Vectorial velocity composition within the channel.

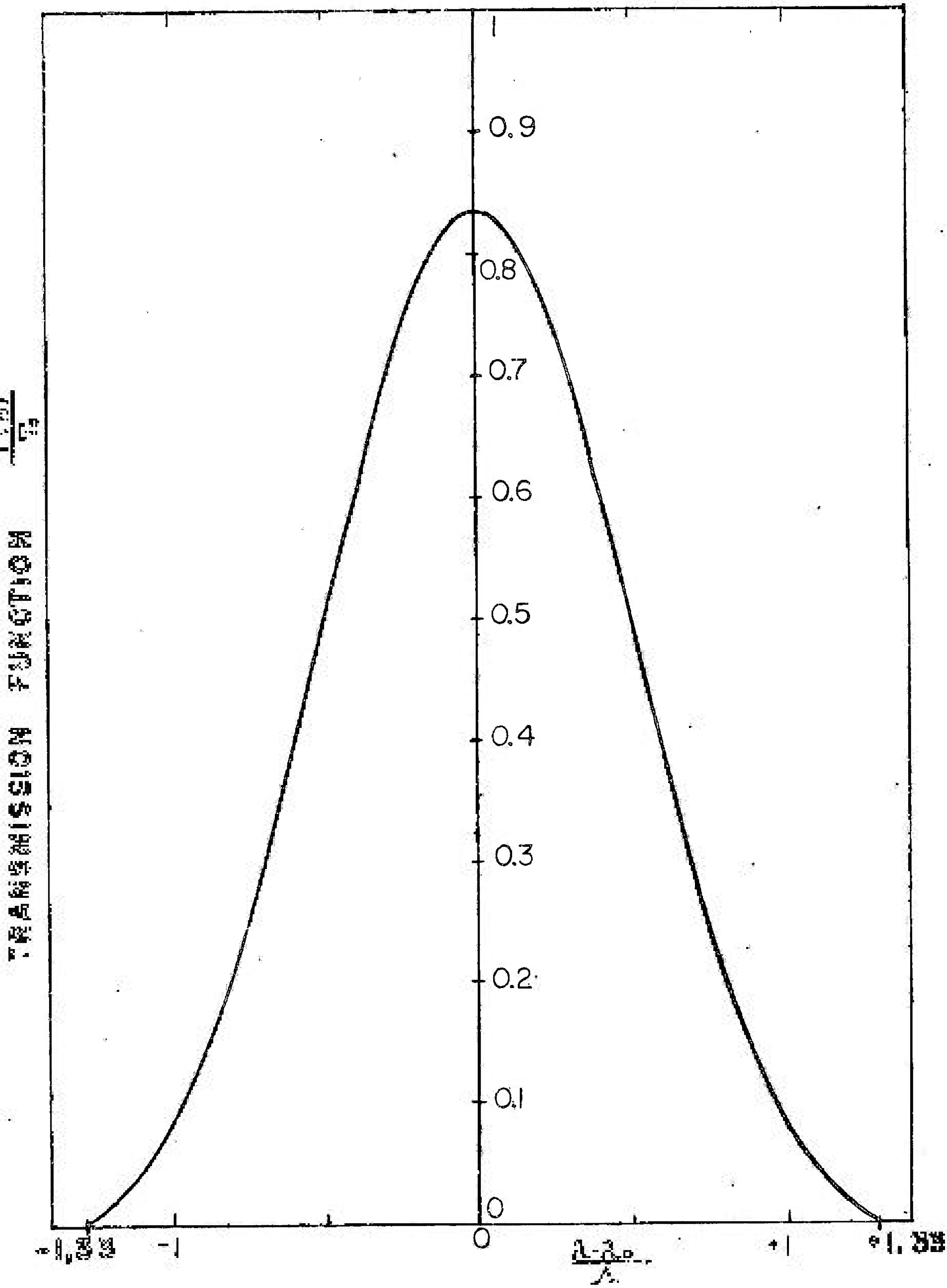
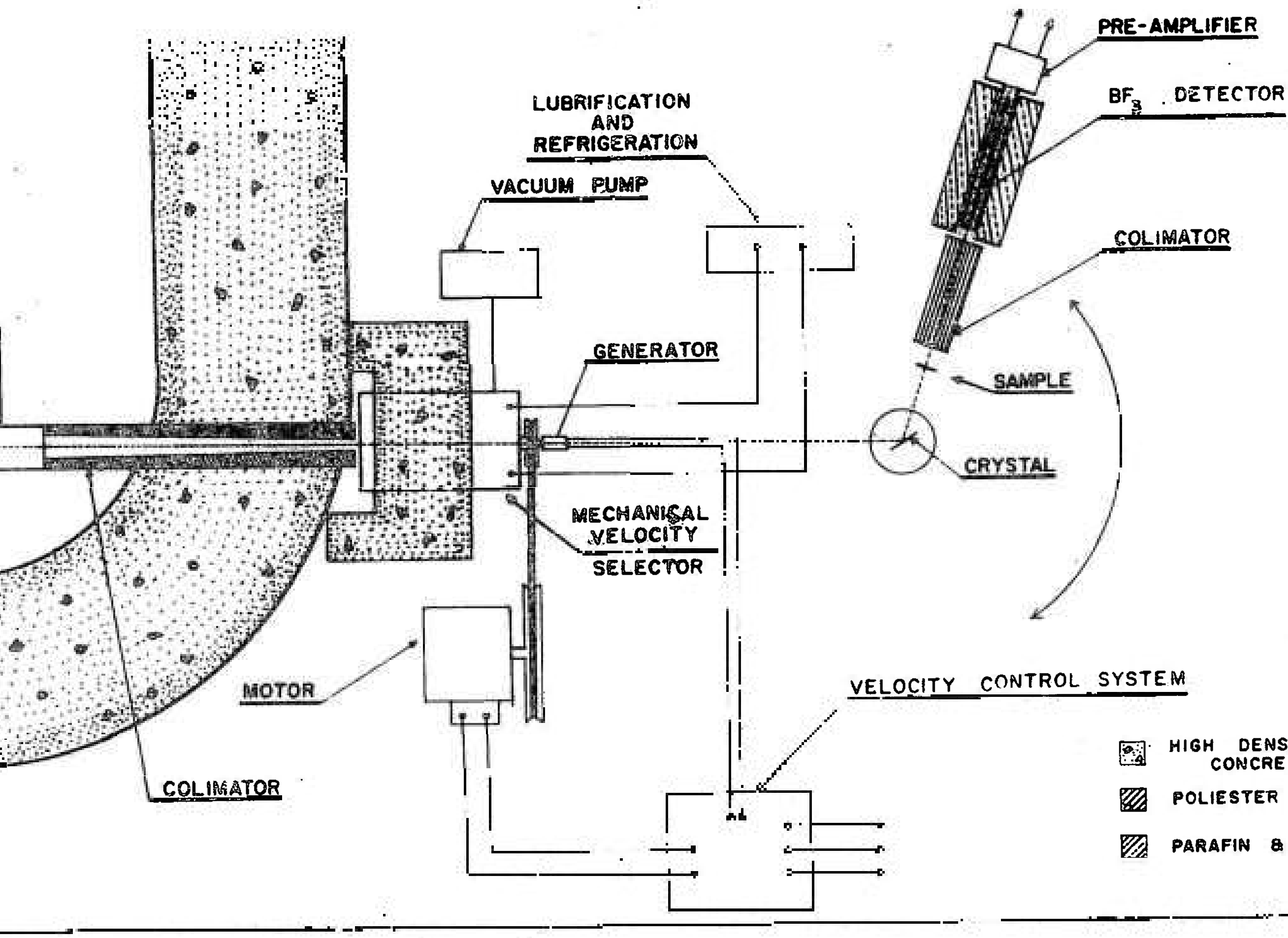
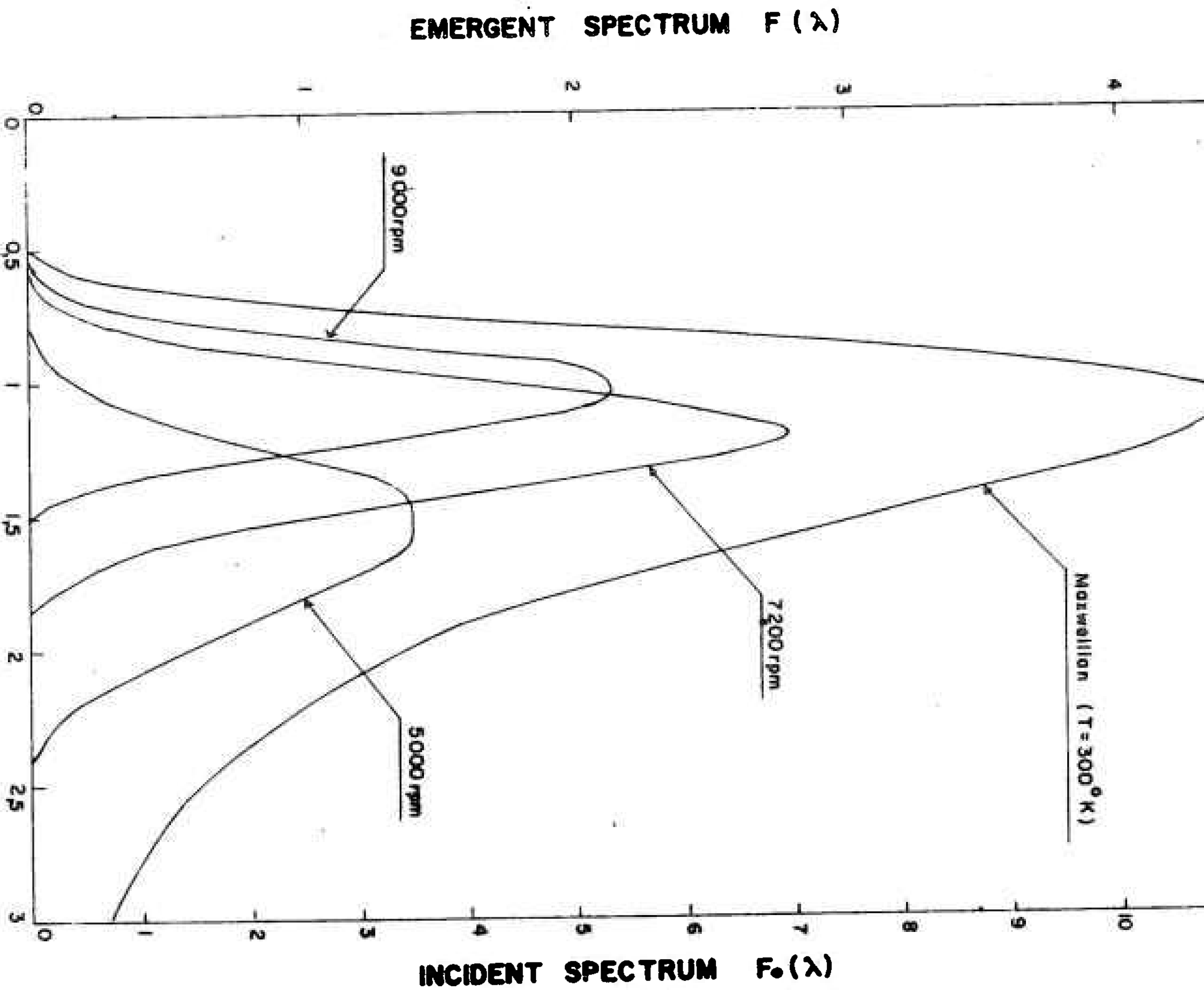


Figure 3 - Transmission function for P= .33 .



PRE-AMPLIFIER
BF_3 DETECTOR
LUBRIFICATION
AND
REFRIGERATION
VACUUM PUMP
COLIMATOR
GENERATOR
SAMPLE
CRYSTAL
MECHANICAL
VELOCITY
SELECTOR
MOTOR
VELOCITY CONTROL SYSTEM
COLIMATOR
HIGH DENS
CONCRE
POLIESTER
PARAFIN &


EMERGENT SPECTRUM F (λ)
INCIDENT SPECTRUM F₀ (λ)
9000 rpm
7200 rpm
5000 rpm
Maxwellian (T = 300° K)

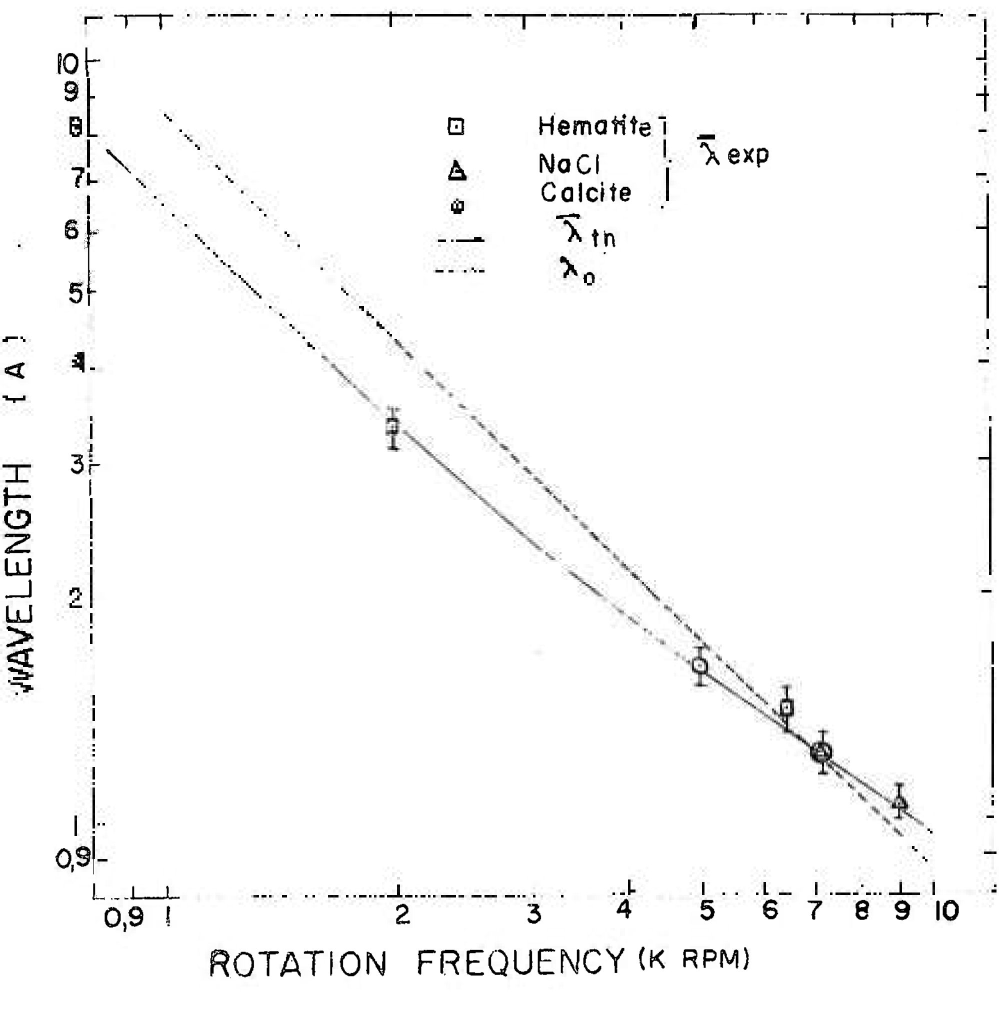
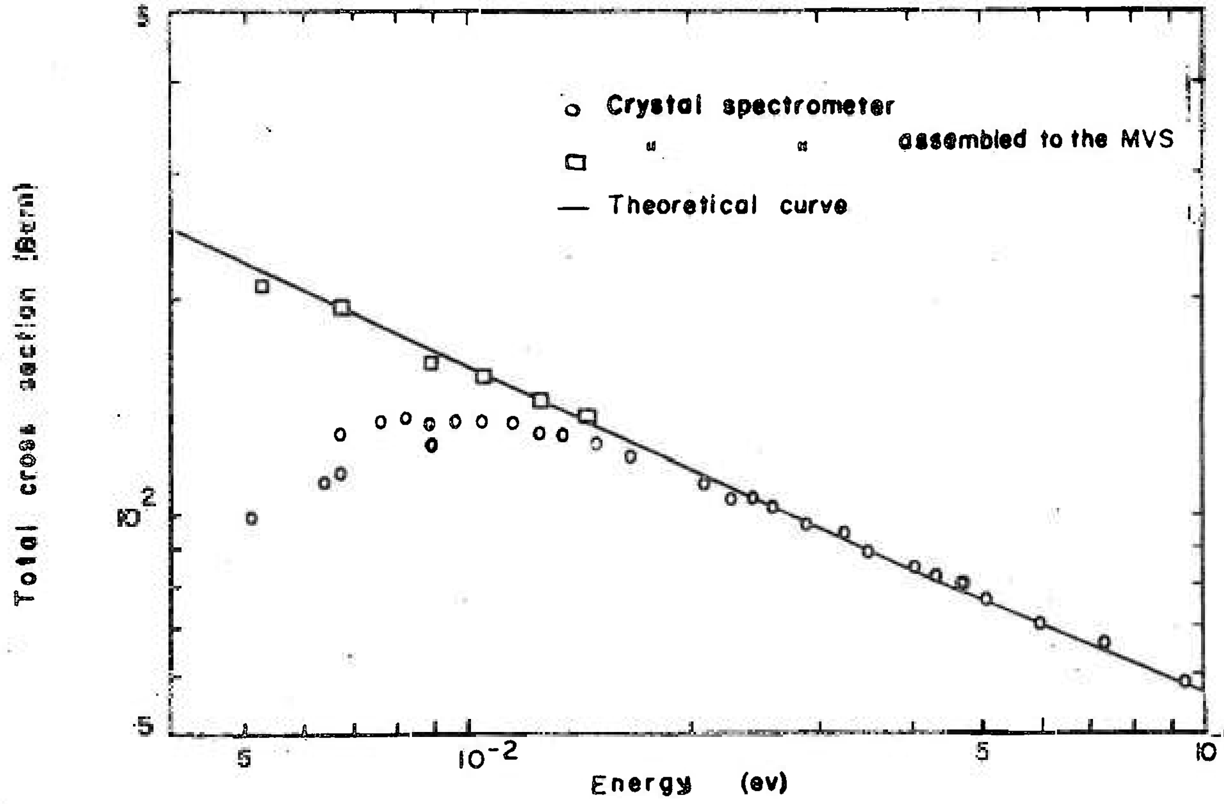


Figure 6 — Theoretical and experimental curve calibration.



Crystal spectrometer
" " assembled to the MVS
Theoretical curve
Total cross section (Barn)
10^2
5
10^{-2}
5
10^{-1}
Energy (ev)