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IDAHO NUCLEAR CORPORATION
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ABSTRACT

A nearly monochromatic beam of 25-keV neutrons has been obtained from the HG-5 beam facility of the Materials Testing Reactor (MTR) by using a combination of natural iron, aluminum and sulphur filters. The actual peak energy of the beam is 24.5 ± 0.5 keV and the full-width-at-half-maximum (FWHM) is approximately 1.8 keV. This well-collimated beam has an initial diameter of 3.50 inches and a neutron flux of approximately 2×10^5 neutrons/cm^2/sec. The gamma-ray field associated with the beam was found to be less than 20 mr/hr. The neutron energy spectrum of the beam has been analyzed from 1 keV to 1 meV with a proton-recoil spectrometer. The raw proton-recoil data which were obtained with a hydrogen-filled detector and a multichannel pulse-height analyzer were used to "optimize" the beam, i.e. to obtain the maximum ratio between the magnitude of the 25 keV neutron peak and the general "background" level. The best "signal-to-background" ratio was obtained with 26.84" of Fe (99.72%), 8.22" of Al (99.99%), and 2.31" of S (99.9%). The "background" intensity has been reduced to approximately 2% of the 25 keV neutron-intensity.

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Test reactors such as the Materials Testing Reactor (MTR) were designed to provide very intense sources of neutrons for experimental applications. Since the MTR was the first test reactor to be built, its design was very versatile with provisions for beam holes, thermal columns and pneumatic rabbit facilities to mention a few. Consequently, many complex and diverse neutron physics experiments can be conducted concurrently without necessarily requiring that the reactor be shut down in order to make changes in the experiment. The MTR offers unique opportunities to conduct experiments and perform measurements which could not be done otherwise. This manuscript will describe how the MTR was utilized to develop and then produce an intense beam of 25-keV neutrons.

Most experiments involving reactor development and neutron physics research have one thing in common. They are generally neutron energy dependent and information concerning the neutron environment of the experiment is essential. This information can be very gross such as integrated neutron flux values or very detailed such as a complete neutron energy spectrum. For example, many reactor oriented experiments are conducted inside of test reactors near the fuel in order to take advantage of the high neutron fluxes which exist there. The neutron energy spectrum inside a reactor is very complex and practically impossible to measure in complete detail. Therefore, if an experiment is conducted inside a test reactor the neutron energy dependence must be of secondary importance since only integrated neutron flux values are presently available. For most neutron physics experiments, the measurements are not meaningful unless the energies of the neutrons involved are known or can be determined.

Outside a reactor's sealed pressure vessel conditions are vastly improved for obtaining neutron energy information since many ingenious electronic and mechanical devices can be used. The MTR has beam ports which allow neutrons to escape from the core or shielding and drift to different types of spectrometers and monochromators. The fast-neutron chopper facility of the MTR makes use of these neutron beams to measure total neutron cross sections. Crystal spectrometers are used in solid state physics studies at the MTR to obtain monochromatic neutrons from these inhomogeneous neutron beams. Proton-recoil spectrometers which are at a disadvantage inside of a reactor due to high counting rates and interfering gamma rays are extremely useful outside a reactor under controlled neutron and gamma-ray conditions as will be demonstrated.

The scandium 2-keV neutron beam facility of the MTR first demonstrated the practicality and usefulness of a new concept for obtaining intense sources of monochromatic neutrons. The large interference dip in the cross section of ^{45}Sc was found to be 0.05 barns at 2 keV(1) which encouraged the development of a 2-keV neutron facility at the MTR.(2) The low interference dip in the total cross section of iron at approximately 25 keV indicated that iron would also make a good filter. The relatively low cost of a good grade of natural iron made it a promising filter material for obtaining 25-keV neutrons. In addition, it was felt that the transmission properties of aluminum and sulphur were such that a combination of these three elements would filter or remove practically all neutrons of energies other than 25-keV from the beam.

CHAPTER II

DESCRIPTION OF EXPERIMENTAL EQUIPMENT

Three major pieces of experimental equipment were employed in the development of the 25-keV neutron beam. A fast-neutron chopper was used in a feasibility study of the individual and combined transmission properties of iron, aluminum and sulphur. A proton-recoil spectrometer was used to measure the neutron energy spectrum of the beam transmitted by the finished filter pieces in the HG-5 beam hole of the MTR. Finally, a CDC 1604 digital computer was utilized to calculate transmission values based on experimental cross-section data for various thicknesses of Fe and Al. The computer was also used to reduce the raw proton-recoil data obtained with the proton-recoil spectrometer and calculate a differential neutron energy spectrum.(3)

The Fast-Neutron Chopper

The MTR fast-neutron chopper uses a time-of-flight technique to determine total neutron cross sections as a function of neutron energy.(4) A rotor with eight slits equally spaced every 45° chops the neutron beam into eight bursts per revolution of the rotor. The time-of-flight of the neutrons present in each burst is then determined with a timing system which consists of a light pulse, banks of $^{10}BF_3$ proportional counters,(5,6,7) and a TMC 4096-channel analyzer. The light pulse traverses the rotor 45° to the neutron beam(8) to prevent radiation damage to the photocell. The light pulse is used to initiate the timing sequence of the analyzer. Five banks of 16 $^{10}BF_3$ counters per bank detect the arrival of the neutrons at the end of a 20 meter flight path. The individual ionization pulses due to the $^{10}B(n,\alpha)^{7}Li$ reactions in the counters are amplified and sent to the analyzer where they accumulate counts in time channels according to their relative time of arrival.

The Proton-Recoil Spectrometer

The proton-recoil spectrometer used in this experiment consisted of a coaxial cylinder-type detector and a 256-channel pulse-height analyzer. The 256-channel TMC model CN-110 pulse-height analyzer is a mobile unit which can be placed near the experiment for easier manipulation. The detector was filled to 200 cm Hg pressure of hydrogen gas. A single anode wire with a diameter of 0.001" is located along the axis of the 1" diameter stainless steel tube. The effective length of the proportional counter was three inches. A preamplifier is mounted to the counter to provide additional amplification of the recoil-proton pulses.

Neutrons which enter the sensitive region of the hydrogen-filled detector and collide with the hydrogen molecules transfer a portion of their energy to recoil-protons. The energy of each recoil-proton is then dissipated in the chamber (providing the track lengths are small compared with the dimensions of the chamber) through electromagnetic interactions with the gas which produces ionization. The negatively charged ions are accelerated towards the positively charged anode wire causing secondary ionization (gas multiplication) to occur. The transient collection of these negatively charged particles at the anode causes pulses in the electronics which, if accepted, are recorded in memory channels of the analyzer according to the voltage (height) of each pulse.

The Collimator and Filter Pieces

The collimator which would be used to prevent neutrons from being scattered into the beam was constructed primarily of 4142 stainless steel. One end of the collimator was fitted with a 6" long brass section and the other end was fitted with a 6.25" long nickel section to prevent transmission of 25 keV neutrons through the collimator. In order to prevent "streaming" of neutrons between the surface of the filter pieces and the collimator, the bore of the collimator was stepped to accomodate progressively larger diameter filter pieces. The overall dimensions of the collimator were 6.875" O.D. x 46.5" long. The inside diameter of the bore was 3.50" at the exit and 2.78" at the entrance.

The iron filter pieces were machined from cold drawn Armco magnetic ingot iron (99.72%). The aluminum filter pieces were machined from 1100 Al (99.99%) and the sulphur pieces were cast from sulphur flakes (99.9%). Table I shows the dimensions of the filter pieces.

The CDC 1604 Computer and PSNS Computer Code

The complex task of transforming the integral raw proton-recoil spectrum into a differential neutron flux spectrum was accomplished with a CDC 1604 computer and computer program. The PSNS (Proton Spectrum to Neutron Spectrum) computer code(3) accepts a set of pulse-height distribution measured at various voltages with two counter types (optional) and provides a neutron energy spectrum as output. A plot of the recoil-proton and neutron flux energy spectrum can also be obtained from the output data with a calcomp program.(3)

TABLE I

Dimensions and Types of Filter Pieces Used in Study

Type	No.	Dia.	Thickness
Fe	3	2.990"	2.66"
Fe	3	3.115"	2.66"
Fe	3	3.240"	2.66"
Fe	3	3.365"	3.50"
Fe	3	3.490"	2.06"
Al	1	2.990"	2.66"
Al	1	3.115"	2.66"
Al	1	3.240"	2.66"
Al	1	3.365"	3.50"
Al	1	3.490"	2.06"
S	1	3.36"	2.75"
S	1	3.36"	1.75"
S	1	3.36"	2.31"

CHAPTER III

THE EXPERIMENT

The Preliminary Fast Chopper Runs

The presence of a relatively sharp decrease in the neutron cross section of a material followed by a neutron scattering resonance is a nuclear phenomenon aptly described by the Breit-Wigner theory.(9) (Also, see Appendix A.) The interference dip (called a "window") which occurs in the total neutron cross section of natural iron at approximately 24 keV(10) is due to the large scattering resonance of ^{56}Fe at 27.9 keV(10) (see Figure 1). The total cross section of ^{56}Fe has been measured at 24 keV using time-of-flight techniques and a minimum value of approximately 0.16 barns has been reported.(10)

The ^{56}Fe isotope, then, would be an excellent filter material except for the prohibitive expense involved. For practical reasons, it was decided to investigate the possibility of using a natural grade of iron. Since natural iron consists of ^{54}Fe (5.82 o/w), ^{56}Fe (91.66 o/w), ^{57}Fe (2.19 o/w), ^{58}Fe (0.33 o/w) and in most commercial grades a host of impurities, the total cross section of natural iron will be higher than 0.16 barns at 24 keV.(10)

It was decided to test a sample piece of cold drawn Armco magnetic ingot iron. A spectrachemical analysis of the sample indicated that it was 99.7 o/w iron. A 2.25" diameter by 14.5" long bar of Armco iron was placed in the sample changer of the MTR fast-neutron chopper facility. The time-of-flight spectrum data which were obtained during this run are shown in the top curve of Figure 2. These results

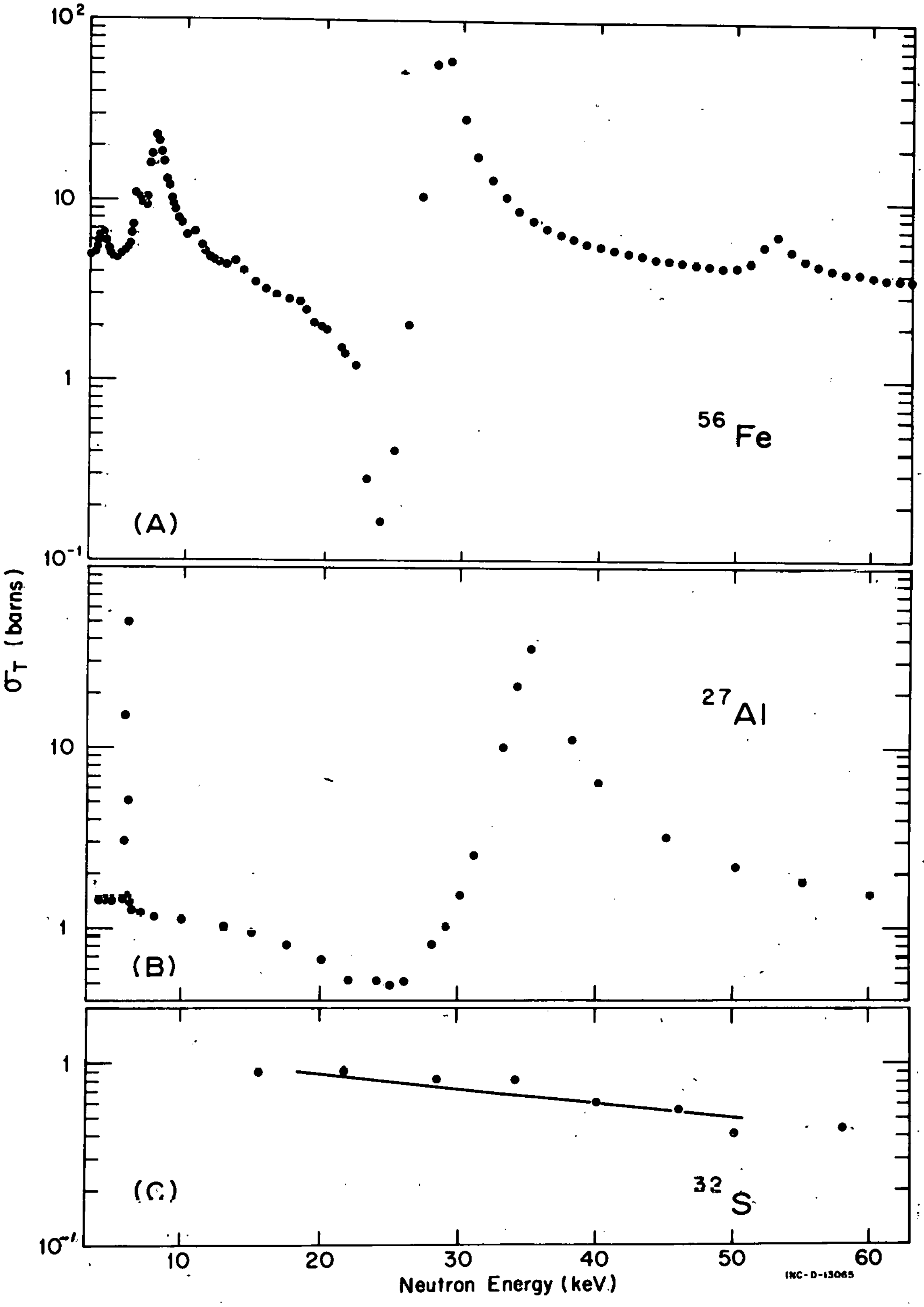

Figure 1. Total Neutron Cross Sections of Iron, Aluminum and Sulphur from 5-60 keV.

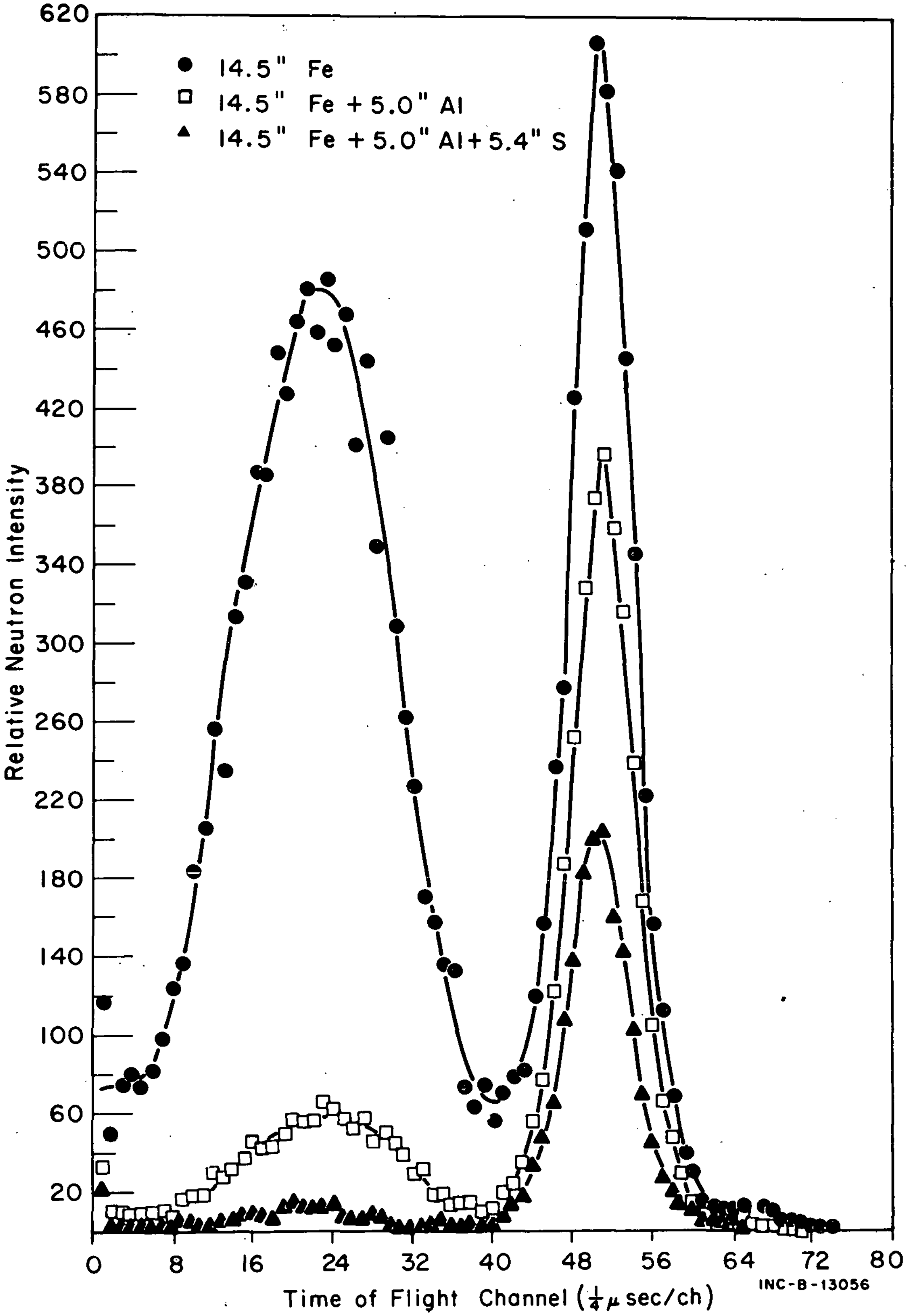

Figure 2. Fast-Neutron Chopper Time-of-Flight Spectrum Data for Different Combinations of Fe, Al and S.

were encouraging because of the magnitude of the transmission peak at approximately 25 keV.

A 5" thick piece of aluminum (99.99 o/w) was then placed in the sample changer with the 14.5" of iron to investigate their combined transmission properties. The results of this second fast chopper run are plotted as the intermediate curve in Figure 2. The 5" of aluminum removed approximately 90% of the high energy neutron component and about 30% of the 25-keV neutrons.

A 5.375" thick piece of sulphur (99.9 o/w) was then placed in the sample changer with the iron and aluminum pieces and time-of-flight spectrum data were taken for this combination of filters with the fast chopper. The sulphur piece was effective in reducing the high energy neutron component as shown in the data plotted in Figure 2; however, the 25-keV neutron peak was reduced an additional 50%.

The Computer Studies

It was apparent from the fast chopper runs that the Armco ingot iron could be used to produce a reasonably monochromatic beam of 25-keV neutrons providing the proper amounts of aluminum and sulphur were used to remove most of the higher energy neutrons. Unfortunately, this approach would also reduce the potential 25-keV neutron flux. Therefore, it was decided to conduct a computer simulated study of reactor neutron transmission as a function of Fe and Al thicknesses in order to arrive at an "optimum" combination. Figure 3 shows the type of neutron transmission information which was obtained from computer calculations.

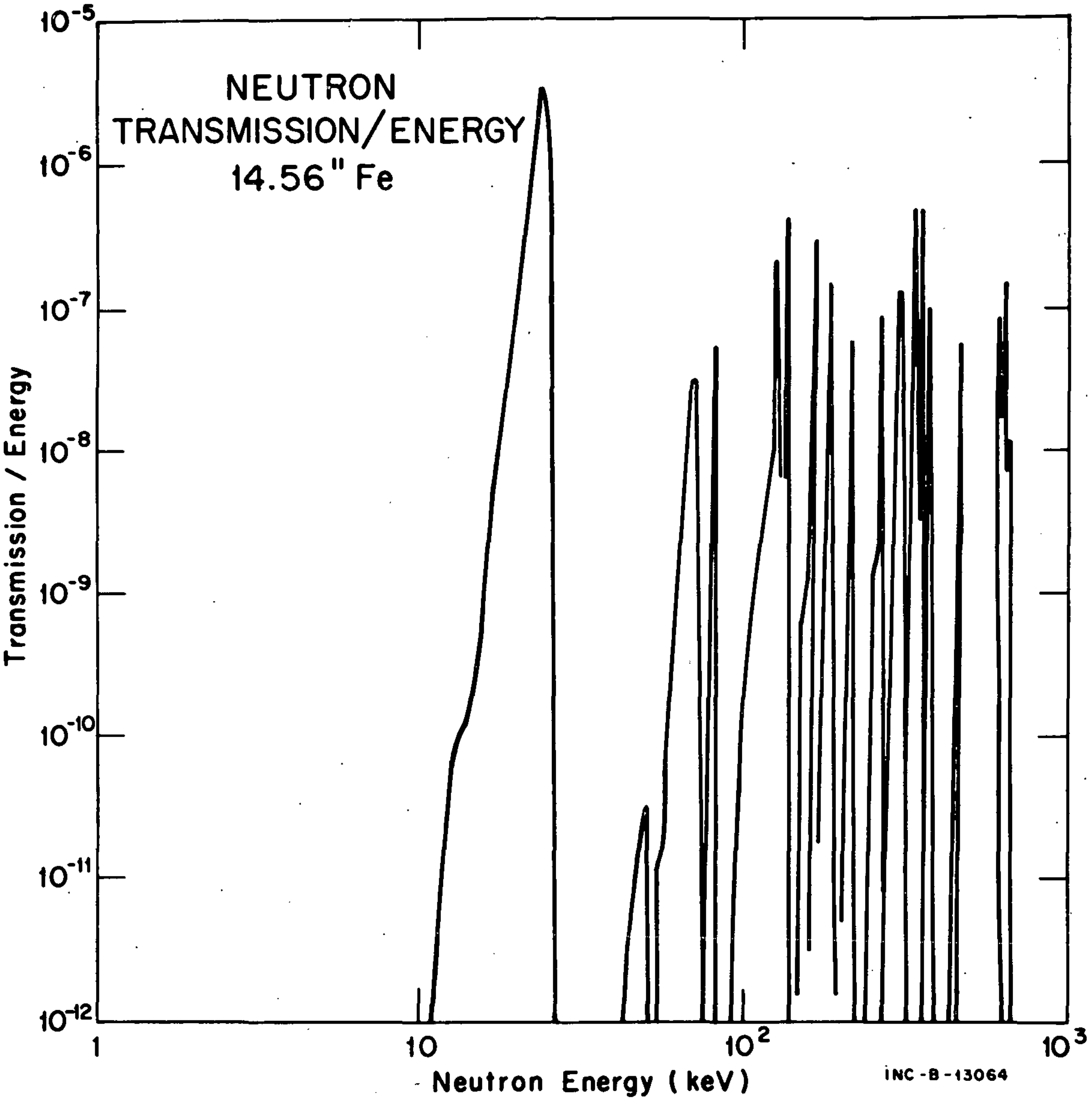

Figure 3. Computer Calculated Transmission/Energy Data for 14.5" of Fe. The Spectrum Shows the Relative Intensities of the Numerous Iron "Windows".

Although the computer results were difficult to interpret in terms of which combination of Fe and Al would provide an optimum ratio between the 25-keV neutron peak and the general neutron "background", they were informative. The areas of the transmission peaks were integrated by hand using the trapezoidal method. Table II lists the results and compares the "signal-to-background" ratios.

The computer results were based on total neutron cross-section information. Sulphur was not included because it was felt that the amount which would be used would be minor compared with the relative amounts of Fe and Al.

Experimental Arrangement in HG-5

After the collimator was placed in the HG-5 beam hole facility of the MTR the chamber was filled with 40.62" of Armco iron. A hydrogen-filled proportional counter was then mounted on a stand and placed 3" from the face of the collimator and oriented with its axis perpendicular to the beam. A neutron catcher was placed in the projected path of the beam approximately 4 feet from the hydrogen-filled detector. The neutron catcher consisted of a lead brick core 24" x 24" x 36" long surrounded by a borated polyethylene cave 6" thick. The surface of the shielding which faced the detector was covered with a .040" thick sheet of cadmium to prevent thermal neutrons from being scattered back to the detector. Figure 4 shows the experimental arrangement with the collimator and filters in the HG-5 beam hole of the MTR.

Optimizing the Filters

The HG-5 beam facility of the MTR has a lead "door" which effectively stops neutrons and gamma rays coming from the reactor.

Table II

Results of Computer Transmission Calculations

Filters	ϕ_{25} keV	$\int_{>30\ \text{keV}} \phi(E)\,dE$	$\phi_{25} \Big/ \int_{>30} \phi(E)\,dE$
14.5" Fe	1.43×10^{-2}	1.02×10^{-2}	1.40
14.5" Fe 5" Al	7.95×10^{-3}	0.524×10^{-3}	15.2
36" Fe 6" Al	1.03×10^{-4}	0.170×10^{-4}	6.07
36" Fe 12" Al	6.77×10^{-5}	0.194×10^{-5}	35.0
24" Fe 6" Al	1.04×10^{-3}	0.0901×10^{-3}	11.6

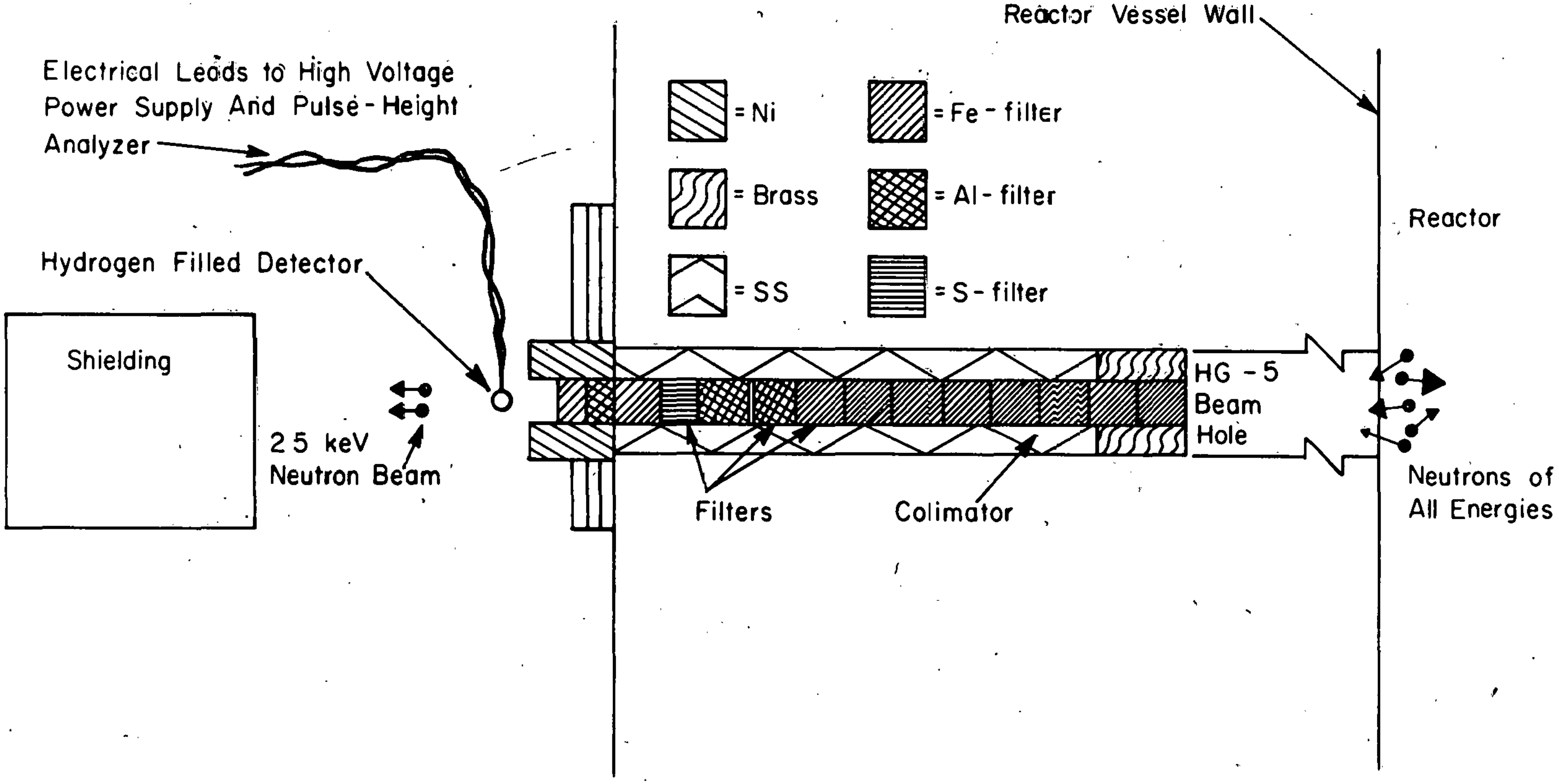

Figure 4. Experimental Arrangement of the Iron Filter Located in the Horizontal Beam Hole (HB-5) of the MTR Reactor.

This door had to be opened manually with a socket wrench prior to taking proton-recoil data. A typical set of proton-recoil measurements required eight runs at different voltage settings in order to cover the entire neutron spectrum from 1 keV to 1 MeV. For a particular voltage setting the upper and lower electronic discriminators will allow proton-recoil ionization pulses of a particular voltage (height) range to be analyzed. Increasing or decreasing the anode voltage simply increases or decreases the gas multiplication of the detector; therefore, different energy groups of recoil-proton pulses can be analyzed in this manner. Approximately two hours of total counting time were required to accumulate sufficient counting statistics.

The proton energy spectrum which was obtained with 40.62" of Armco iron is shown in Figure 5. These data have been processed using the PSNS computer code which also calculates the neutron energy spectrum which is shown in Figure 6. These neutron spectral data agree qualitatively with time-of-flight measurements(11), i.e., the energies of the transmitted neutrons correspond with the energies of the interference dips in the iron cross section. All of the proton-recoil spectrometer data were taken in the single parameter mode since the gamma-ray effects(3) had been observed to be small. Gamma effects increase the "background" in the energy region below approximately 20 keV (see Figure 6).

Figure 7 shows the neutron energy spectra which were obtained from proton-recoil spectrometer data taken in the HG-5 beam with the following filters: (1) 40.62" Fe; (2) 37.96" Fe, 2.66" Al; (3) 30.96" Fe, 6.16" Al, 2.75" S. These three spectra have been normalized to the same peak intensity at 25 keV and the data below 15 keV have been

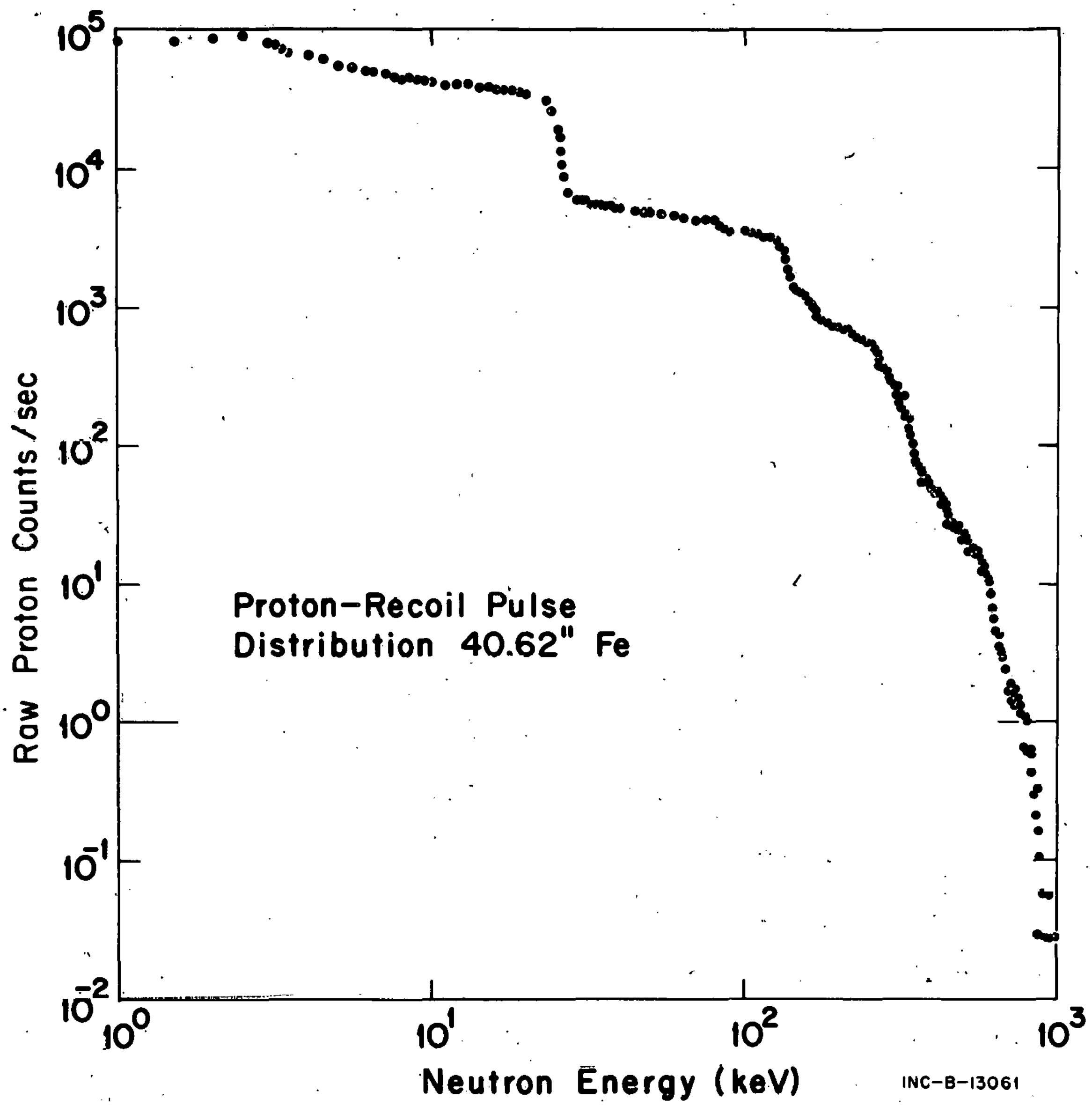

Figure 5. Computer Treated Proton-Recoil Integral Spectrum Obtained from the Neutron Beam Transmitted through 40.62" of Fe.

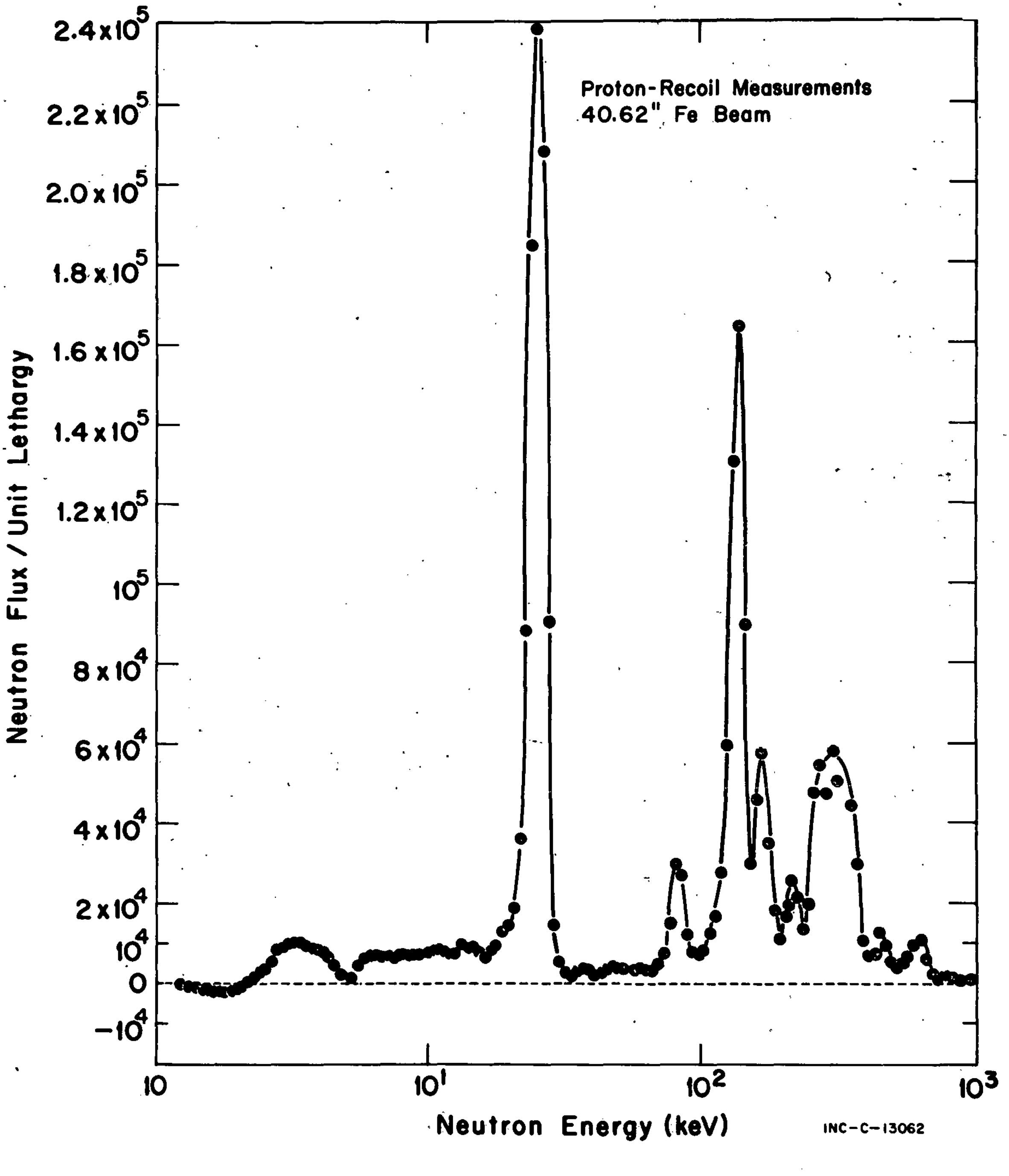

Figure 6. Neutron Energy Differential Spectrum of the Neutron Beam Transmitted through 40.62" of Fe.

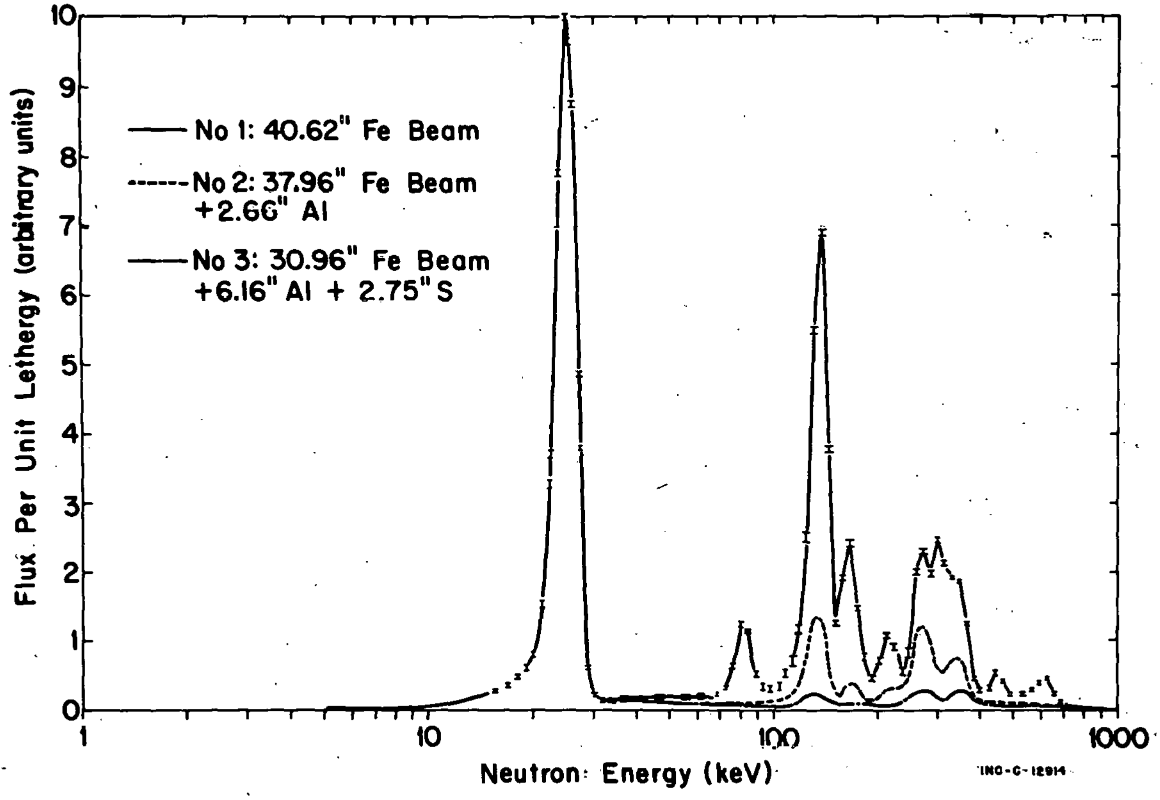

Figure 7. The Neutron Differential Spectra for Different Combinations of Iron, Aluminum and Sulphur.

extrapolated (gamma effects). The FWHM of the 25-keV neutron peak was found to be 4.3 keV which is in reasonable agreement with the predicted resolution of the detector (3.75 keV)(12).

As indicated in Figure 7, various thicknesses of Fe, Al and S filters were used in an effort to "optimize" or enhance the magnitude, M, of the 25-keV neutron peak relative to the "background", B. Table III compares the relative magnitudes, M, and ratios, R, of the total proton-recoil pulses collected in channel 60 and channel 80 at an anode voltage of 2800 V. For example, in Figure 8 channel 60 falls at about 25 keV. Similarly, at channel 80 the proton-recoil pulse distribution has a constant slope which indicates that the neutron spectrum is at the "background" level in this region.(12) The magnitude of the pulse distribution can be used to determine the magnitude of the neutron flux.(13) Therefore, this was a useful means of interpreting the effects of changing the amounts of filter material in the beam.

A criterion for optimizing the beam was to obtain the highest value for the ratio, R, and then obtain the highest value for the magnitude, M, while maintaining R relatively constant. The "optimum" beam under these conditions was obtained with 26.84" of Fe, 8.22" of Al and 2.31" of S. Figure 8 shows an integral distribution spectrum of the "optimized beam".

Neutron Flux and Gamma-Ray Measurement

The 25-keV neutron flux which was obtained with 26.84" of Fe, 2.31" of S and 8.22" of Al was measured with an indium foil. The indium foil was 3 cm x 3 cm in area and 0.0127 cm thick. When exposed

Table III

Iron Filter "Optimizing" Data

Inches of Fe	Inches of Al	Inches of S	M (C/sec)	R(M/B)
40.62	none	none	43	3.6
37.96	2.66	none	47	11.1
35.90	2.66	none	56	11.7
33.84	2.66	none	68	11.7
34.46	2.66	2.75	56	16.5
32.40	2.66	2.75	65	16.3
32.40	4.72	2.75	58	20.1
30.96	6.16	2.75	60	21.9
30.96	6.16	1.75	64	21.4
30.96	8.82	1.75	49	23.4
30.96	8.82	none	58	18.0
28.90	8.82	1.75	60	22.1
28.90	6.16	1.75	79	23.8
27.46	6.16	1.75	79	19.9
28.40	6.16	1.75	77	20.8
28.90	6.16	1.75	72	21.3
26.84	8.22	2.31	76	25.4
25.40	8.22	2.31	90	23.0

A sample of the type of information which was obtained with a proton-recoil spectrometer is listed above. For each combination of Fe, Al and S shown above a value was obtained for M and R; where M was the relative number of proton-recoil counts stored in channel 60 of the analyzer minus the "background", B, which was the number of counts stored in channel 80. R = M/B.

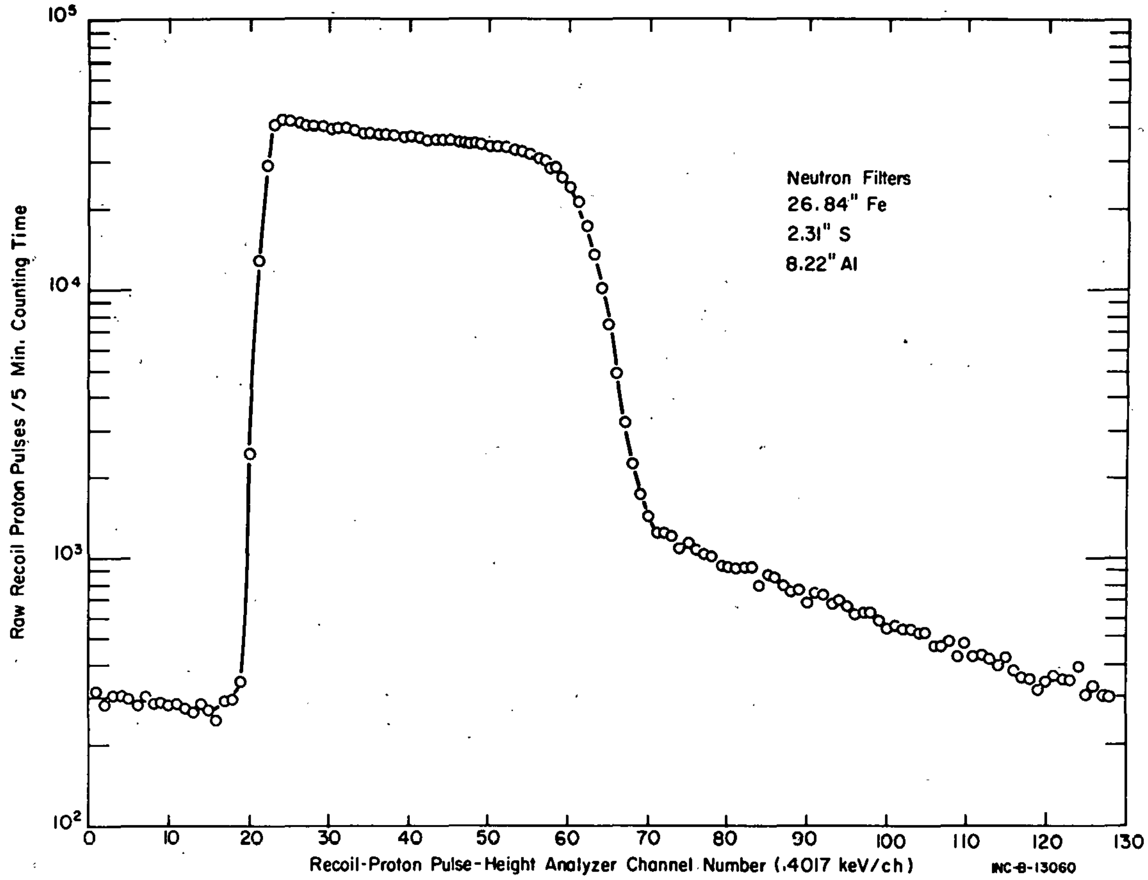

Figure 8. Raw Proton-Recoil Pulse-Height Integral Distribution Obtained Using an Anode Voltage of 2800 V.

to the 25-keV neutron beam for a period of 7 hours the saturated 54-minute ^{116m}In gamma-ray activity was sufficiently intense to be analyzed with a 3" x 3" NaI crystal and a 512-channel pulse-height analyzer. Assuming a ^{115}In(n,γ)^{116m}In cross section of 0.77 barns$^{(10)}$ at 24-keV, a neutron flux value of 2.15×10^5 n/cm^2/sec was obtained.

The gamma-ray component of the 25-keV neutron beam was found to be less than 20 mr/hr. Kodak AA x-ray film was exposed in the beam for 16 hours. The film is relatively insensitive to neutrons; however, some neutron effects can be expected from (n,p) reactions in the film. A calibrated ^{60}Co source was used to calibrate the x-ray film. It was found that a 300-mr dosage of ^{60}Co gamma rays caused equivalent darkening of the film. Therefore, the exposure rate for the film in the 25-keV neutron beam was less than 20 mr/hr.

CHAPTER IV

DISCUSSION OF RESULTS

The optimization of the iron filtered MTR neutron beam has produced a new research tool capable of providing experimentalists with a high intensity source of monochromatic 25-keV neutrons ($\sim 10^7$ n/cm^2/sec).

The concept which was used to obtain the 25-keV neutron beam was new (using an interference dip and the inherent cross section of several select materials to filter all but the 25-keV neutrons from a non-homogeneous beam). For practical reasons it was desirable to obtain the highest possible 25-keV neutron flux from a particular neutron source. It was soon discovered, however, that any attempts to remove the high energy neutron component from the beam with aluminum and sulphur filters resulted in a decrease of the 25-keV neutron flux. Therefore, it was necessary to arrive at some sort of a compromise.

It was found that a proton-recoil spectrometer was the best means of "optimizing" the filters. Although computer studies of neutron transmission through Al and iron had been made, in general, these results were difficult to interpret. The cross-section errors which were involved coupled with computer code treatment of the data made this type of analysis very unsatisfying. Fortunately, the proton-recoil spectrometer offers a much quicker and more meaningful method for obtaining representative neutron transmission data.

The FWHM of the 25-keV neutron peak shown in Figure 7 was found to be 4.3 keV which is in reasonable agreement with the predicted resolution of the hydrogen-filled detector (3.75 keV).(12) The actual FWHM of the 25-keV neutron peak will be a function of the amounts of filter material in the neutron beam. The calculated FWHM of the 25-keV neutron peak transmitted by 26" of ^{56}Fe is 1.8 keV. The increased width of the 25-keV neutron peak and the increased gamma ray intensity caused by reducing the amounts of filter material in the beam were additional factors to be considered during the selection of an "optimum" filter arrangement.

CHAPTER V

SUMMARY

The results of this study show that a near monochromatic source of 25-keV neutrons can be obtained with a neutron flux of approximately 10^7 n/cm^2/sec by utilizing one of the high intensity beam holes of the MTR. For example, the thermal neutron source flux in HG-5 is approximately 2×10^{13} n/cm^2/sec compared with a thermal neutron source flux of approximately 3×10^{14} n/cm^2/sec in the HB-3 beam hole of the MTR. The indium-cadmium ratios in HG-5 and HB-3 are approximately 8 and 4, respectively; therefore, the magnitude of the 1/E segment of the source neutron energy spectrum is approximately 35 times greater in HB-3. A 25-keV neutron flux of 2×10^5 n/cm^2/sec was obtained from HG-5. The gamma-ray component in the 25-keV neutron beam was found to be less than 20 mr/hr. The proton-recoil spectrometer was found to be the best means of optimizing the beam. The best "signal-to-background" ratio was obtained with 26.84" of Fe, 8.22" of Al and 2.31" of S. The "background" (neutrons having energies other than 25 keV, gamma rays, counter effects) intensity has been reduced to less than 2% of the 25-keV neutron intensity. Examples of experiments that will be performed using the 25-keV beam are listed in Appendix B.

APPENDIX A

DERIVATION OF NEUTRON SCATTERING EQUATIONS

The basic Breit-Wigner theory yields for a single isolated nuclear level a value for the scattering cross section of slow ($\ell = 0$) s-wave neutrons.

$$\sigma_s(E) = 4\pi\,\lambda_o{}^2 g \left| \frac{\Gamma_n/2}{E-E_o + i\Gamma/2} + \frac{R}{\lambda_o} \right|^2 + 4\pi(1-g)R^2 \qquad \text{(A-1)}$$

where

$$g = 1/2\left[1 \pm \frac{I}{2I + 1}\right]$$

I is the spin of the target nucleus,

E_o is the resonance energy,

$2\pi\lambda_o$ is the wavelength of the neutron with kinetic energy, E_o,

R is the nuclear radius,

Γ_n is the partial level width for neutron emission at E_o, and

Γ is the total level width (FWHM).

Expanding expression (A-1) gives:

$$\sigma_s(E) = 4\pi\lambda_o{}^2 g \left(\frac{\Gamma_n/2}{E-E_o + i\Gamma/2} + \frac{R}{\lambda_o}\right)\left(\frac{\Gamma_n/2}{E-E_o - i\Gamma/2} + \frac{R}{\lambda_o}\right) + 4\pi(1-g)R^2$$

$$\sigma_s(E) = 4\pi\lambda_o{}^2 g \left[\frac{(\Gamma_n/2)^2}{(E-E_o)^2 + (\Gamma/2)^2} + \left(\frac{R\Gamma_n/2}{\lambda_o}\right) \frac{2(E-E_o)}{(E-E_o)^2 + (\Gamma/2)^2} + \left(\frac{R}{\lambda_o}\right)\right]^2$$

$$+ 4\pi(1-g)R^2$$

$$\sigma_s(E) = \frac{4\pi\lambda_o{}^2 g(\Gamma_n/2)^2}{(E-E_o)^2 + (\Gamma/2)^2} + \frac{4\pi\lambda_o g\; R\; \Gamma_n\; (E-E_o)}{(E-E_o)^2 + (\Gamma/2)^2} + 4\pi R^2 \qquad \text{(A-2)}$$

The first term in expression (A-2) is commonly referred to as the "resonance scattering term". The second term is the "interference scattering term" and the last term is the constant "potential scattering term".

Differentiating expression (A-2) with respect to the neutron energy, E, and setting the differential equal to zero results in a quadratic equation.

$$\frac{d\sigma_s(E)}{dE} = -\frac{[8\pi\lambda_o^2 g(\Gamma_n/2)^2 + 8\pi\lambda_o gR\Gamma_n(E-E_o)]\,(E-E_o)}{[(E-E_o)^2 + (\Gamma/2)^2]^2} +$$

$$+\frac{4\pi\lambda_o gR\Gamma_n}{(E-E_o)^2 + (\Gamma/2)^2} = 0$$

or

$$(E-E_o)^2\; 8\pi\lambda_o gR\Gamma_n + (E-E_o)\; 8\pi\lambda_o^2 g(\Gamma_n/2)^2 -$$

$$-\,4\pi\lambda_o gR\Gamma_n\,[(E-E_o)^2 + (\Gamma/2)^2] = 0$$

then

$$(E-E_o)^2 + \frac{\lambda_o\Gamma_n}{2R}(E-E_o) - (\Gamma/2)^2 = 0$$

$$E-E_o = -\frac{\lambda_o\Gamma_n}{4R} \pm 1/2\sqrt{\left(\frac{\lambda_o\Gamma_n}{2R}\right)^2 + \Gamma^2}.$$

A maximum and a minimum value* in the single-level scattering cross section, $\sigma_s(E)$, exist at

$$E = E_o - \frac{\lambda_o\Gamma_n}{4R}\left[1 \mp \sqrt{1 + \left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2}\,\right] \tag{A-3}$$

---

*A second derivative would be necessary to show this.

The energy at which the minimum scattering cross section occurs is given by:

$$E_{min} - E_o = -\frac{\lambda_o\Gamma_n}{4R}\left[1+\sqrt{1+\left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2}\right]$$

The minimum scattering cross section from equation (A-2) is:

$$\sigma_s(E_{min}) = 4\pi R^2 - \frac{\pi\lambda_o{}^2 g\Gamma_n\sqrt{1+\left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2}}{\left(\frac{\lambda_o\Gamma_n}{4R}\right)^2\left[1+\sqrt{1+\left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2}\right]^2+(\Gamma/2)^2}$$

$$\sigma_s(E_{min}) = 4\pi R^2\left\{1-\frac{4g\left(\frac{\lambda_o\Gamma_n}{4R}\right)^2\sqrt{1+\left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2}}{\left(\frac{\lambda_o\Gamma_n}{4R}\right)^2\left[1+\sqrt{1+\left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2}\right]^2+(\Gamma/2)^2}\right\}$$

$$\sigma_s(E_{min}) = 4\pi R^2\left\{1-\frac{4g\sqrt{1+\left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2}}{2+2\sqrt{1+\left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2}+2\left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2}\right\}$$

$$\sigma_s(E_{min}) = 4\pi R^2\left\{1-\frac{2g}{\left[1+\left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2\right]^{1/2}+1}\right\} \qquad \text{(A-4)}$$

if $\left(\frac{2R\,\Gamma}{\lambda_o\Gamma_n}\right)^2 << 1$

then

$$\left[1 + \left(\frac{2R\Gamma}{\lambda_o\Gamma_n}\right)^2\right]^{1/2} = 1 + 1/2 \left(\frac{2R\Gamma}{\lambda_o\Gamma_n}\right)^2 + \ldots$$

and

$$\sigma_s(E_{min}) \approx 4\pi R^2 \left\{1 - \frac{2g}{2 + 2\left(\frac{R\Gamma}{\lambda_o\Gamma_n}\right)^2}\right\}$$

Similarly, if $\frac{R\Gamma}{\lambda_o\Gamma_n} << 1$

$$\sigma_s(E_{min}) \approx 4\pi R^2 \left\{1 - g\left[1 - \left(\frac{R\Gamma}{\lambda_o\Gamma_n}\right)^2 + \ldots\right]\right\} \qquad \text{(A-5)}$$

For ^{56}Fe

$I = 0$

$g = 1$

$A = 56$

$R = 5.75 \times 10^{-13}$ cm

$\Gamma = 1601$ eV

$\Gamma_n = 1600$ eV

$\lambda_o = 2.74 \times 10^{-12}$ cm

$E_o = 27.9 \times 10^3$ eV

then

$$\left(\frac{2\Gamma R}{\lambda_o\Gamma_n}\right)^2 = (0.42)^2 = 0.176$$

From equation (A-4)

$$\sigma_s(E_{min}) = 4.16 \times 10^{-24} \left(1 - \frac{2}{2.08}\right) \text{cm}^2$$

$$\sigma_s(E_{min}) = 0.160 \times 10^{-24} \text{ cm}^2 = 0.160 \text{ barns}$$

or from equation (A-5)

$$\sigma_s(E_{min}) \approx 4\pi R^2 \left(\frac{R\Gamma}{\lambda_o \Gamma_n}\right)^2 \qquad \text{(A-6)}$$

$$= 4.16 \times 10^{-24} \ (0.044) \text{ cm}^2$$

$$= 0.183 \text{ barns}$$

Also, from equation (A-3)

$$E_{min} = (27.9 \times 10^3 - 3.96 \times 10^3) \text{ eV}$$

$$E_{min} = 23.9 \text{ keV}$$

It is of interest to investigate the conditions under which the scattering cross section might be zero.

From (A-4), (A-5) and (A-6) it can be seen that

$$\sigma_s(E_{min}) = 0$$

when

$$g = 1$$

and

$$\frac{R\Gamma}{\lambda_o \Gamma_n} = 0$$

since

$$\frac{\Gamma}{\Gamma_n} > 1$$

and

$$\frac{R}{\lambda_o} = \frac{1.5 \times 10^{-13} \ A^{1/3}}{4.57 \times 10^{-10}} \sqrt{E_o}$$

Then

$$\sigma_s(E_{min}) = 0$$

when

$$E_o = 0.$$

APPENDIX B

APPLICATIONS FOR A 25-keV NEUTRON BEAM

Neutron Cross Section Measurements

The potential applications for a beam facility capable of providing an intense flux of 25-keV neutrons are numerous. The beam can be used to measure total and partial cross sections at 25 keV. Although gamma-neutron sources have been used for that purpose(14,15), the improved intensity and resolution of the 25-keV filtered neutron beam will provide additional information in this area.

A second area of application which is related to the measurement of neutron capture cross sections is in astrophysics. The peak of the neutron Maxwellian distribution that occurs in a certain class of stars (red giants, s-process) is located at approximately 20-30 keV.(16,17) Therefore, an investigation of the neutron capture cross sections in this energy region is of considerable importance to the theories that predict the creation of the elements. The information which could be obtained from this intense source of 25-keV neutrons would be most valuable to this nucleosynthesis study.

Prompt Gamma-Ray Studies

The extremely low gamma-ray field associated with the 2-keV scandium filtered neutron beam(2) and the 25-keV iron filtered neutron beam facilities of the MTR makes them ideal for measuring the prompt gamma rays from neutron capture in various materials.(18) Since a better understanding of nuclear structure and the fission process might be obtained by prompt gamma-ray investigations as a function of incident neutron energies(19), filtered beam facilities are currently being utilized for this purpose at the MTR.

Measurements of Resonance Neutron Parameters

The power reactors of the future will probably be fast breeder reactors. The neutron energy spectra of breeder reactors peak in the resonance neutron region. Therefore, it is necessary to obtain more accurate measurements of average resonance neutron parameters which might affect the safety and operation of breeder reactors.(2) The scandium 2-keV neutron beam facility has already been used to measure the change in neutron cross section as a function of sample temperature for several materials(2) and is currently being used to measure the neutron multiplication factor, eta, of ^{239}Pu at 2 keV.(20) Similar measurements with the 25-keV neutron beam are being planned because of the relative importance of neutrons at that energy in a breeder reactor.

Neutron Therapy

Another important area of application for filtered neutron beams may be in the field of medicine. Considerable effort has been devoted by members of the medical profession to the development of a technique for treating malignant tumors with neutron therapy.(21) The treatment involves the assimilation of tumor-seeking chemicals which have a relatively large neutron-fission cross section and the subsequent bombardment of the tumor with neutrons. Recoiling fission fragments destroy cancer cells in their process of slowing down either through ionization or collisions. Since it is important to the technique that the thermal neutron density be concentrated at the tumor rather than at the skin surface (which would be the case with a thermal neutron source), a neutron source with a mean energy in the low keV energy region is necessary.

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