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LINEAR ACCELERATOR PROJECT

AEC Contract No. AT(11-1)-3058

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for

October 1, 1971 - September 30, 1972

LINEAR ACCELERATOR PROJECT

Rensselaer Polytechnic Institute
Troy, New York 12181

Erwin R. Gaerttner
Project Director

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In this contract year, October 1, 1971 - September 30, 1972, the major effort at the Rensselaer LINAC was in three areas:

(1) measurement, analysis and theory of neutron cross sections necessary for the design of the LMFBR, (2) measurement, analysis and theory of fast neutron spectra in large homogeneous systems consisting of materials of interest in LMFBR and (3) the further development of interactive graphics for data analysis.

Neutron capture and total cross sections in the keV range were continued for isotopes of reactor structural materials. The ^{240}Pu capture, fission and total cross-section data were analyzed and published in Nuclear Science and Engineering, 49, 153 (1972). High energy total cross-section measurements from 0.5 - 20 MeV were extended to include ^3He , ^6Li and ^{238}U ; the results for ^1H and ^2H were published in Nuclear Physics, A183, 51 (1972). The total cross section in iron at the 24.3 keV minimum was measured to be $\sigma_t = 0.41 \pm 0.03\text{b}$ and measurements of the higher energy iron minima enabled accurate evaluations of the ENDF/B files. Using an iron-filtered beam and neutron time-of-flight, relative capture cross sections of several reference isotopes were measured at the 24 keV minimum. Fission multiplicity $\bar{\nu}$ measurements were completed for ^{233}U and ^{235}U and work begun on $\bar{\nu}$ of ^{239}Pu . Doppler and resonance self-protection measurements were made for depleted uranium over a wide range of temperature. Non-statistical properties of nuclei were investigated theoretically to shed light upon the intermediate structure observed in keV cross section and upon correlation observed between neutron and radiative widths.

Analyses of the fast neutron spectra measurements in iron and depleted uranium have been completed and published respectively in Nuclear Science and Engineering, 47, 329 (1972) and 49, 330 (1972). Similar analyses for the aluminum data are in progress. Preliminary studies of fast neutron transport across a material interface (Al-Fe) have been completed. Detailed investigations of position-dependent, fast neutron angular flux spectra in metallic

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sodium are in progress. Fast neutron targets with increased neutron yield at low neutron energies (<1 keV) have been developed to facilitate spectrum measurements in the region where Doppler is significant.

In the analytical area, high order anisotropic group constants have been generated, transport calculations performed, and comparisons with experiment made for several data files for the materials of interest. In addition, a technique for handling elastic scattering matrices has been developed which greatly reduces the overall computer time associated with processing ENDF/B data and generating group constants.

Work is in progress on an interactive graphics system utilizing a PDP-15 computer at the RPI LINAC site in telephone communication with the CDC-6600, the AEC Computing Center, at NYU. Communication has been satisfactory in the batch mode; the next step is remote utilization of NYU's new time-sharing/batch system through our graphics system.

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NEUTRON CROSS SECTIONS

NEUTRON CROSS-SECTION PROGRAM

The experimental cross-section program this year focussed on six research areas, (1) keV capture and total cross sections, (2) MeV precision total cross sections, (3) keV differential scattering cross sections, (4) iron-filtered beam 'point' cross sections, (5) fission multiplicity measurements, and (6) temperature and sample thickness dependence of transmission and self-indication measurements. The highlights from these areas are presented below:

(1) KeV Capture and Total Cross Sections—Measurements were carried out this year on enriched samples of ^{54}Fe , ^{58}Fe , ^{61}Ni and ^{64}Ni using the 1.25-meter-diameter capture detector (at 25 meters) and the ^{10}B -NaI transmission detector (at 28 meters).

Although these measurements were not completed this year, they have already contributed toward a knowledge of the energy location and isotopic assignment of the resonances of these nuclei. Measurements have commenced on ^{242}Pu with the 1.25-meter-diameter detector, and preliminary results indicate that both the capture cross section and the subthreshold fission cross sections should be obtained up to several tens of keV.

A paper describing similar capture and fission measurements upon ^{240}Pu up to several tens of keV has been published this year in Nuclear Science and Engineering.¹ A keV energy measurement of the ^2H total cross section was carried out to supplement the MeV measurements, and a marked increase was obtained in the cross section below 200 keV over what had been published earlier; this new information sheds light on the discrepancy of previously reported scattering lengths for deuterium.

(2) MeV Precision Total Cross Section—This year total cross section measurements from 0.5 to over 20 MeV were completed for ^2H , ^3He , ^4He , ^6Li and ^{238}U . This completes the total cross section measurement of all stable isotopes of the first three elements, although it is planned to repeat the ^6Li measurements when a purer sample is available. The excellent results obtained with

^{238}U show that precision MeV total cross-section measurements can be made on heavy as well as light nuclei using the neutron time-of-flight method.

(3) KeV Differential Scattering Cross Sections—The iron data have been corrected for multiple scattering and reduced to differential scattering cross sections from approximately 60 to 600 keV. Modifications were made to the apparatus this year which increased the data rate by an order of magnitude, thus making it possible to carry out scattering measurements on separated isotopes.

(4) Iron-Filtered-Beam 'Point' Cross Sections—Analysis was completed upon the cross-section minima occurring in iron. A result of 0.41 ± 0.03 barn is obtained for the 24.3 keV minimum, in agreement with recent ORNL measurements. Comparison of our data and ENDF/B-III show that the latter data set has iron minima (above 28 keV) which are still too low in cross section. Radiative capture measurements were carried out near 24 keV using an 8-inch-thick iron filter, the 1.25-meter-diameter capture detector, and thin samples of In, Ta, Au and ^{238}U (99.8%). The effective capture cross sections near 24 keV were determined in the ratio $\tilde{\sigma}_Y(\text{In}) : \tilde{\sigma}_Y(\text{Ta}) : \tilde{\sigma}_Y(\text{Au}) : \tilde{\sigma}_Y(^{238}\text{U}) = (0.89\text{b}) : (0.98\text{b}) : (0.68\text{b}) : (0.47\text{b})$. This filtered beam technique, when combined with low-energy saturating resonance capture and high resolution keV capture, should provide precise (2 to 4%) capture cross section 'point' cross sections at ~24 keV to which white-source measurements may be compared and normalized.

(5) Fission Multiplicity Measurements—Fission multiplicity

($\bar{\nu}$) measurements have been completed from thermal energies to several tens of electron volts for ^{233}U and ^{235}U . For both of these nuclei $\bar{\nu}$ appears to be constant over the thermal energy region (~0.01 to 0.10 eV) to within $\pm 0.1\%$. The resonance $\bar{\nu}$ values appear to vary by more than is expected for a Gaussian spread about a constant $\bar{\nu}$ value, although this spread is less than 1% for ^{235}U and 1.5% for ^{233}U . Measurements have also just commenced for ^{239}Pu from thermal energies to 100 eV.

(6) Temperature- and Sample-Thickness-Dependence of Transmission and Self-Indication Measurements—Measurements have been completed on depleted uranium (99.8% ^{238}U) at 77°K, 295°K and 973°K from a few tens of eV to over 100 keV. The data in the unresolved resonance region were analyzed both by generating statistical ensembles of resonances and by analytically integrating over the distribution functions for the resonance parameters. The experimental results in the unresolved region could generally be fit by extrapolating the resolved resonance region parameters into the unresolved region, but these measurements showed up significant local fluctuations which are not predictable by the simple extrapolation.

Theoretical efforts in support of the cross-section program concentrated on increasing our calculational ability to perform (1) optical model calculations, (2) shape analysis for total neutron cross-section resonance parameters, (3) the identification of nonstatistical intermediate structure in measured cross sections, and (4) analysis of correlations between neutron and radiative widths.

(1) Optical Model Calculation—Spherical optical model calculations have been performed using both the JUPITØR and ABACUS codes to calculate s- and p-wave neutron strength functions and the potential scattering radius as a function of mass number. In searching for global optical model parameters that simultaneously fit experimental data on these three quantities, in particular the deep p-wave strength function minima we observed, it was found necessary to introduce a partial-wave-dependent imaginary surface potential strength term, W_ℓ , to produce very good simultaneous fits. Theoretical work is underway to see whether the ratio (W_1/W_0) obtained in fitting has any physical basis.

(2) Shape Analysis for Total Neutron Cross-Section Resonance Parameters—A shape analysis code has been written which fits transmission spectra via a multi-level reduced R-matrix formalism for the total neutron cross section. A first attempt at calculating the experimental resolution function was completed, mathematically treat-

ing the polyethylene moderator by a time-dependent leakage probability calculation. The shape analysis code has been used to adjust the potential scattering radii in the Columbia resonance parameter set for elemental iron to fit exclusively the total neutron cross-section minima about 24 keV. In conjunction with the iron minima work, an area analysis code was also written and used to check the accuracy of tabulated data files for predicting iron total cross-section minima. We are now in the process of programming the PDP-15 for interactive graphics shape fitting to transmission spectra.

(3) Nonstatistical Intermediate Structure in Measured Cross Sections—Cross-section data analysis for nonstatistical intermediate structure has been implemented by a Monte Carlo calculation. Studies of s-wave elastic neutron scattering on ^{40}Ca revealed the likelihood of nonstatistical intermediate structure in the experimental data of the $\frac{1}{2}^+$ scattering channel. Doorway state mechanisms proposed have been supported by coupled channel calculations using JUPITOR.

(4) Analysis of Correlations Between Neutron and Radiative Widths—Neutron cross-section measurements on chromium isotopes have indicated a positive correlation between neutron and radiative widths. Such correlations are expected for nuclei which exhibit strong single-particle behavior for a given reaction channel, let us say s-wave neutrons making a transition to a single-particle p-state via an E1 gamma-ray emission. The isotopes ^{57}Fe , ^{53}Cr and ^{61}Ni all have strong (d,p) strengths with low-lying p-states and hence are candidates for possibly exhibiting correlations. Comparison of calculated and experimentally fitted radiative widths for these isotopes was therefore made, reduced width factors obtained and conclusions drawn on the importance of channel versus compound nucleus reactions.

REFERENCE:

1. Nucl. Sci. Eng., 49, 153 (1972).

CAPTURE, FISSION AND TOTAL CROSS SECTIONS OF ^{240}Pu

R. W. Hockenbury, W. R. Moyer and R. C. Block

These measurements are completed and a paper has been accepted for publication by Nuclear Science and Engineering.¹ Resonance parameters were obtained from 20 to 500 eV.² Average parameters are given in Table 1. After our measurements, the ^{240}Pu samples were loaned to Harwell in order to check their previous normalization. The revised Harwell results³ for the eV resonance led to a renormalization of the Geel data.³ The radiation widths obtained by all three laboratories are now in agreement as shown in Table 1.

Additional analysis has been performed on the subthreshold fission data. Fission areas for individual resonances are given in Table 2 for the three lowest subthreshold fission groups. Figure 1 shows details of the 1400 eV region as seen in capture and fission. There is generally a 1:1 correspondence between peaks in capture and fission with possibly a doublet observed in fission near channel 800. The most striking differences between the capture and fission data is the prominent peak in fission near channel 837.

Figure 2 shows the 1900 eV region with the relative amount of capture and fission changing from resonance to resonance.

Table 3 gives energies and fission areas of higher energy subthreshold fission groups. The average level spacing of the group is 710 ± 200 eV. This compares to 13.7 eV for the average spacing of resonances below 500 eV seen in capture and transmission. In the double-humped potential barrier model for subthreshold fission, the 13.7 eV spacing corresponds to the level density in the first minimum (Class I) and 710 eV to the level density in the second minimum (Class II). The excitation energy corresponding to 710 eV is about 3.1 MeV indicating that the second minimum is about 2.3 MeV above the first minimum in the potential barrier.

Difficulties present in the present fission measurements are resolution and sensitivity. Resolution effects are noticeably present in the 1400 eV group. Since the fission area of a resonance is approximately proportional to $g \frac{\Gamma_n \Gamma_f}{\Gamma}$, for the case where $\Gamma_f \gg (\Gamma_n + \Gamma_v)$, the measured area or sensitivity is proportional to $g \Gamma_n$. Thus the smaller experimental peaks sometimes correspond to the larger fission widths.

REFERENCES:

1. R. W. Hockenbury, W. R. Moyer and R. C. Block, Nucl. Sci. Eng., 49, 153 (1972).
2. R. W. Hockenbury, J. D. Boice, W. R. Moyer and R. C. Block, Conf.-710301, Vol. 2, Physics (710-4500).
3. H. Weigmann, private communication.

FIGURE CAPTIONS

- Fig. 1 Capture and Fission Yield/N near 1400 eV in ^{240}Pu .
 Fig. 2 Capture and Fission Yield/N near 1900 eV in ^{240}Pu .

Figure 1

Figure 2

Table 1

Average Radiation Width and Strength Function for ^{240}Pu

	s wave		p wave	
	$\langle \Gamma_{\gamma} \rangle$ (eV)	S^0	$\langle \Gamma_{\gamma} \rangle$ (eV)	S^1
RPI	0.0295 ± 0.0015^a	$1.1 \times 10^{-4}^a$	0.030^b	$2.8 \times 10^{-4}^b$
Geel	0.032 ± 0.003^c	$1.05 \times 10^{-4}^d$	-	-
Harwell	0.031^e	-	-	-

a. From resolved resonance parameters below 500 eV.

b. Determined by fitting the averaged experimental capture cross section from 6 to 30 keV.

c. H. Weigmann - revised value - private communication.

d. W. Kolar and K. H. Böckhoff, J. Nuclear Energy 22, 299 (1968).

e. For the 20 eV resonance, note c.

Table 2. ^{240}Pu Fission

ENERGY (eV)	$g \frac{\Gamma_n \Gamma_f}{\Gamma}$ (meV)	
	RPI	MIGNECO & THEOBALD
749	8.11	5.36
782	4.03	2.50
788	6.76	5.14
810	9.43	8.32
820	1.41	0.82
1404	20.73	-
1427	3.56	2.30
1449	2.32	-
1841	8.06	7.99
1871	1.66	-
1915	27.92	14.98
1953	33.84	20.71
2033	0.90	5.54

Table 3. ^{240}Pu -Areas of Subthreshold Fission Groups

<u>E</u> <u>(eV)</u>	<u>A_f</u> <u>(bn-eV)</u>
793	154.8
1420	77.1
1930	153.7
3000	-
4970	31.8
5130	57.9
5310	78.7
6570	132.7
7060	35.5
7520	82.0
8130	53.6
8920	72.0
10200	50.4

NEUTRON CAPTURE AND FISSION CROSS SECTIONS OF ^{242}Pu

R. W. Hockenbury and R. C. Block

The ^{242}Pu sample has been prepared¹ for cross-section measurements and canned in Al. New photomultiplier bases and a new preamplifier are being tested for these measurements since the ^{242}Pu is so radioactive. Foreground and background measurements² have been made to determine the counting rates for various linac operating conditions. Resonance structure and subthreshold fission groups below 3 keV were observed in our preliminary measurements to be similar to that previously reported.³⁻⁶ The present measurements will concentrate on the region from 3 to 60 keV.

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1. Oak Ridge National Laboratory.
2. Linear Accelerator Project Progress Report, April - June 1972, C00-3058-21.
3. N. J. Pattenden, International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, p. 93 (1965).
4. T. E. Young and S. D. Reeder, Nucl. Sci. Eng., **40**, 389 (1970).
5. D. W. Gergen and R. R. Fullwood, Nucl. Phys. **A163**, 577 (1971).
6. G. F. Auchampaugh, J. A. Farrell and D. W. Bergen, Nucl. Phys. **A171**, 31 (1971).

NEUTRON CAPTURE AND TOTAL CROSS SECTIONS OF ^{54}Fe , ^{58}Fe , ^{61}Ni AND ^{64}Ni

R. W. Hockenbury, N. N. Kaushal and R. C. Block

Capture, transmission and neutron flux measurements have been completed on ^{54}Fe , ^{58}Fe , ^{61}Ni and ^{64}Ni emphasizing the energy region from 100 eV to about 35 keV. Figures 1 and 2 show capture and transmission data for ^{61}Ni . Isotopic assignments of resonances have been made (see Tables 1-4). Tables 1 and 2 for ^{54}Fe and ^{58}Fe supersede those previously reported.¹ Note that the 11.2 keV resonance previously assigned to ^{56}Fe is now properly attributed to ^{54}Fe . Also two resonances previously assigned to ^{58}Fe have been deleted. The use of better samples and improved resolution also has caused some modification for ^{61}Ni and ^{64}Ni ; the latest resonance listings are given in Tables 3 and 4.

A series of pulse-height vs. time-of-flight measurements were made on ^{54}Fe , ^{58}Fe , ^{61}Ni and ^{64}Ni in order to determine the detector efficiency for neutron capture in these isotopes. The pulse-height spectrum for the 14.4 keV ^{54}Fe resonance is shown in Fig. 3 and that for the 8.70 keV ^{61}Ni resonance in Fig. 4.

The capture, transmission and pulse-height data are being analyzed in order to obtain resonance parameters and an estimate of p-wave strength functions below about 35 keV.

REFERENCES:

1. R. W. Hockenbury, Z. M. Bartolome, J. R. Tatarczuk, W. R. Moyer and R. C. Block, Phys. Rev. **178**, 1746 (1969).

FIGURE CAPTIONS

- Fig. 1 Neutron Capture Data for ^{61}Ni .
 Fig. 2 Neutron Transmission Data for ^{61}Ni .
 Fig. 3 Neutron Capture Gamma Spectrum for the 14.4 keV ^{54}Fe Resonance.
 Fig. 4 Neutron Capture Gamma Spectrum for the 8.70 keV ^{61}Ni Resonance.

Figure 1

Figure 2

PULSE HEIGHT SPECTRUM FOR NEUTRON CAPTURE
IN FE-54 AT 14.4 KEV

Figure 3

PULSE HEIGHT SPECTRUM FOR NEUTRON CAPTURE
IN NI-61 AT 8.70 KEV

Figure 4

Table 1

 ^{54}Fe

E_o (keV)	E_o (keV)
3.10	23.0
8.10	28.2
9.48	30.6
11.2	35.1
13.5	38.3
14.4	39.1
19.2	

Table 2

 ^{58}Fe

E_o (keV)
0.230
0.359
6.20
10.5
19.2

Table 3

 ^{61}Ni

E_o (keV)	E_o (keV)
1.35	11.4
2.35	11.8
3.14	12.6
3.30	13.3
3.39*	13.5
4.59*	13.9
6.36	14.3
6.46	15.3
7.11	16.7
7.52	17.7
8.70	18.8
9.87	20.0
10.1	20.4
10.9	21.3

*Assignment not definite -
probably ^{61}Ni

Table 4

 ^{64}Ni

E_o (keV)
14.3
25.8
31.8
32-35*
39.2 *
45.8 *
60.0 *
62.4
82.8

*Unresolved

IRON FILTERED NEUTRON BEAMS

R. C. Block, N. N. Kaushal and R. W. Hockenbury

In the previous progress report,¹ a filtered beam capture measurement was reported for In, Ta, Au and ^{238}U (99.8%). An 8-inch-thick iron filter was used for the measurement, and the results were quoted in the ratio of the effective capture cross sections. The effective capture cross section $\tilde{\sigma}_{yi}$ for the i th sample is defined as

$$\tilde{\sigma}_{yi} = \frac{\int_{E_L}^{E_U} \sigma_{yi}(E) \phi(E) dE}{\int_{E_L}^{E_U} \phi(E) dE} \quad (1)$$

where $\sigma_{yi}(E)$ is the capture cross section at energy E , $\phi(E)$ is the relative flux of neutrons transmitted through the iron filter, and E_L and E_U span an energy range below and above the iron window. For these capture measurements E_L and E_U were selected respectively as 20.5 and 25.8 keV. Assuming that the capture cross section has either a simple $1/v$ or $1/E$ dependence in this interval, at what energy is $\tilde{\sigma}_{yi}$ equal to the true cross section? To determine this we must numerically integrate in Eq. (1) the observed flux $\phi(E)$ with a $1/v$ or $1/E$ dependent cross section. The relative flux shape was determined by correcting the filtered-beam counting spectrum observed with a ^{10}B -NaI detector by the detection efficiency (as described in Ref. 2). The relative flux per TØF channel is plotted in Fig. 1 as a function of TØF channel number. Equation (1) was then numerically integrated for both a $1/v$ and a $1/E$ cross-section dependence and for the relative flux of Fig. 1.

For the integration limits of 20.5 and 25.8 keV, the effective cross section $\tilde{\sigma}_{yi}$ is equal to the $1/v$ capture cross section at 23.5 keV and is also equal to the $1/E$ capture cross section at 23.5 keV. Thus, under the assumption that the capture cross sec-

tion near 24 keV falls somewhere between a $1/v$ and $1/E$ dependence, the results of this iron-filtered-beam experiment should be compared to other measured cross sections at 23.5 keV.

In the previous report,¹ the ratio of the effective capture cross sections for these four nuclides was determined. Poenitz³ evaluated the 30 keV capture cross section of Au to be 0.600 barn, and extrapolation to 23.5 keV results in a 0.68 barn cross section. If we assume this 0.68 barn Au capture cross section, we obtain the following ratio of 23.5 effective capture cross sections:

$$\tilde{\sigma}_Y(\text{In}) : \tilde{\sigma}_Y(\text{Ta}) : \tilde{\sigma}_Y(\text{Au}) : \tilde{\sigma}_Y(^{238}\text{U}) = (0.89\text{b}) : (0.98\text{b}) : (0.68\text{b}) : (0.47\text{b}) .$$

This result is good to 4 to 5% (standard deviation).

Future measurements are planned to determine independently the capture cross section of Ta, Au and ^{238}U by normalizing each to a saturated mostly-capture low-energy resonance. In this manner, each effective capture cross section will be "absolute" and not depend on normalization to any other effective capture cross section.

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1. Linear Accelerator Project Progress Report, April - June 1972, 13, COO-3058-21.
2. R. W. Hockenbury, Z. M. Bartolome, J. R. Tatarczuk, W. R. Moyer and R. C. Block, Phys. Rev., **178**, 1746 (1969).
3. W. P. Poenitz, Proc. Conf. Neutron Standards and Flux Normalization, CONF-701002, 320 (1971).

FIGURE CAPTION

Fig. 1 The Relative Neutron Flux Per TOF Channel for Neutrons Transmitted through 8-inch of Armco Iron.

Figure 1

NEUTRON TOTAL CROSS SECTION MINIMA IN ELEMENTAL IRON

K. Alfieri* and P. J. Turinsky

By performing thick sample TØF transmission measurements on high purity Armco iron samples of elemental iron, information has been obtained on which of several existing data files predicts total cross section minima most accurately from 24 keV to about 1 MeV. To illustrate the degree of uncertainty in these data files, Fig. 1 compares the total cross section of elemental iron in the neighborhood of the minima at 24 keV as given by the Penny-Kinney,¹ Version-19² and ENDF/B-III (MAT 1180) data files. We now summarize our conclusions that have already been reported in detail.³

Using the area analysis technique of interpreting the experimental transmission spectra through energy regions containing cross section minima in iron, we concluded that the Penny-Kinney and Version-19 data files both "generally" overestimate the magnitude of the cross section about minima from 24 keV to about 1 MeV. Of the two files, the Version-19 data file is preferred in regard to predicting total cross section minima. With the ENDF/B-III (MAT 1180) data file being identical to the Penny-Kinney data file except for the minima at 24 keV, similar negative conclusions apply to this file for all cross section minima measured except for the minima at 24 keV.

Experimental resolution was not adequate to obtain cross section versus energy information through energy regions of minima except for the lowest observed minima at 24 keV. Assuming delta function resolution, we obtained $(\sigma_t)_{\min} = 0.42 \pm 0.03$ b at $E = 24.3 \pm 0.1$ keV. Figure 2 illustrates our results and contrasts them to the recent Columbia thick sample transmission measurement,⁴ the cross section as calculated using the older Columbia multi-level resonance parameter set⁵ and the ENDF/B-III (MAT 1180) data file. Excellent agreement is obtained with ENDF/B-III (MAT 1180) with regard to the minima at 24 keV.

*Based in part on the Master's Engineering Project of K. Alfieri.

Previously³ it was erroneously reported that via a shape analysis of the transmission spectra ratio (TSR) we could conclude that the Columbia resonance parameter set did not predict minima accurately from 24 to 190 keV, their range of applicability. Upon studying the sensitivity of the TSR to the resolution function we employed in these calculations, the TSR was found very sensitive to the resolution function for these minima except at 24 keV. Hence no meaningful comparison between our measurement and the Columbia resonance parameter set is possible except at the 24 keV minima, where both the TSR study³ and Fig. 2 illustrated disagreement.

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FIGURE CAPTIONS

- Fig. 1 Data File Values of the Elemental Iron Neutron Total Cross Section about 24 keV minima.
- Fig. 2 Comparison of Other Sources and Our Evaluation of the Elemental Iron Neutron Total Cross Section about 24 keV Minima.

Figure 1

Figure 2

TOTAL NEUTRON CROSS SECTION OF DEUTERIUM
FROM LESS THAN 1 KEV TO 1000 KEV*

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ABSTRACT

Total neutron cross sections of deuterium have been measured from less than 1 keV to 1000 keV. The results are compared with a theoretical calculation by Harms and Laroze, and show good agreement. A marked increase in the cross section is observed for decreasing energy below 200 keV. The results are discussed with reference to discrepancies in previously reported scattering lengths.

Introduction

Total neutron cross-section measurements on deuterium provide a sensitive test of the nuclear three-body calculations. They are also useful in reactor physics for the calculation of neutron age in heavy water. However, very little experimental data exists above thermal and below 0.5 MeV neutron energy. Experimental values for these cross sections in this energy range have thus far been mostly based on extrapolation down from data at higher energies. These extrapolations, though consistent with some thermal measurements, are significantly inconsistent with others, which suggest higher values. They also lead to scattering lengths for which it is difficult to reconcile three-body nuclear theoretical calculations. Indeed, there are important discrepancies in the n-D scattering lengths as reported in the literature.¹ Yet it is at these low energies that one has a sensitive test of the calculations. We report here a measurement of the n-D total cross section

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from about 1 keV to 1 MeV, and a comparison with a concurrent theoretical calculation by E. Harms and L. Laroze.² The comparison provides a basis for a proper choice of the n-D scattering lengths.

Experimental Arrangement and Procedure

The basic experimental setup and procedure will be explained briefly.

The electron beam from the Rensselaer LINAC strikes a water-cooled tantalum target producing a white source of neutrons. These neutrons are then scattered by a polyethylene moderator cum scatterer. This scatterer acts as the neutron source for the experiment. The tantalum target is placed so as not to be directly visible to the detector.

The collimated beam of neutrons passes through the deuterium sample located at approximately 10 meters from the source. The sample consists of a 2.5-in. diameter stainless steel cylindrical container with 0.050-in. thick end windows, and is pressurized with 99.8% purity deuterium gas to 1000 ± 2 psi at 0°C . A second identical container was fabricated and evacuated to provide a reference for the cross-section measurement.

The transmitted neutron beam is detected by means of a $^{10}\text{B}_4\text{C}$ sodium iodide detector located at 33 meters from the neutron source. The detector consists of a $\frac{1}{2}$ -in. thick, 12-in. diameter cylindrical slab of a ^{10}B enriched B_4C . This slab is laterally viewed by four 8-in. diameter sodium iodide detectors. These detectors are adjusted to accept the 480 keV γ -ray from the $^{10}\text{B}(\text{n},\alpha)$ reaction.

The data are recorded by means of a PDP-7 on-line computer with 6144 channels available for data. The time-of-flight is measured by means of a 31.25 nsec digital clock interfaced directly to the computer. The pressurized and evacuated samples are mounted on a computer-controlled sample changer. The two samples are alternately interposed into the neutron beam with a cycle time of approximately 3 minutes and data for the pressurized sample and the evacuated sample are separately recorded. One then can calculate the total neutron cross section as a function of energy from these two data.

Filters were interposed in the flight path to reduce the effect of the gamma flash and to eliminate overlap of neutrons from previous neutron bursts. Notch filters were also placed in the beam to estimate the time-dependent background. These studies showed that there was a considerable amount of time-dependent background in the data and that it was not possible to subtract this background precisely enough to arrive at results of the desired accuracy.

In an effort to eliminate the effect of this machine-dependent background, two separate measurements were made. In one of these measurements, an 8-in. thick iron filter was additionally placed in the neutron path and a cross-section measurement was carried out. The effect of this filter is to eliminate most of the neutron beam except at energies corresponding to deep minima in the iron total cross section, such as at 25 keV. The time-of-flight spectrum for the filtered neutron beam is shown in Fig. 1. This greatly reduces the magnitude of the time-dependent background. Furthermore, whatever little background remains can be estimated from the data recorded in between the transmitted peaks since the thick iron filter is essentially black at all energies other than the cross-section valleys. This measurement thus provides a precise measurement of the total cross section at a few energy points corresponding to the iron cross-section minima.

A second measurement made without the iron filter provides a continuous energy measurement. In comparison with the filtered beam results, the magnitude of the cross section was generally low by about 1.5% at very low energies; the difference increasing to about 3% at about 500 keV, and decreasing to about zero at 1000 keV. From these differences a smooth machine-dependent background function is constructed so as to normalize the continuous energy measurement to the precision point measurements obtained from the iron filter beam experiment. One then ends up with a final result which is precisely determined at a few points by virtue of the filtered beam measurement and the shape interpolated between those points by the continuous energy measurement.

The magnitude of the cross sections, and thus the errors in magnitude, are tied to the filtered beam result. Two filtered beam experiments were carried out two months apart under somewhat different experimental conditions. The results agreed to within statistics. Results of a third filtered beam run, this time with a carbon sample, agreed within statistics with standard carbon cross sections. Taken together with the considerations previously discussed, it is felt that the error in magnitude is dominated by the statistical errors in the filtered beam results, as shown in Fig. 2.

Results and Discussion

The final results are shown in Fig. 2. The solid curve is due to a three-body theoretical calculation by Harms and Laroze.² The agreement appears to be good. The fairly rapid decrease in cross section from zero to about 200 keV energy is explained by the dominance of s-wave scattering in this region. The flattening out above 200 keV is explained by the early onset of higher ℓ scattering due to the large interaction radius of the deuteron. Such a phenomenon was already expected by J. S. Story.³ This is in contrast to n-p cross sections, which are dominated by s-wave scattering to over 10 MeV. At lower energies, quartet scattering contributes nearly all of the n-D cross section.

Above 1 MeV, the present experimental cross sections join smoothly, and are consistent with the recent measurements of Clement et al.⁴ and the evaluations by Seagrave,⁵ Horsely and Stewart.⁶ At lower energies, the present measurements are consistent with the thermal measurements (σ_{free}) of Fermi and Marshall,⁷ and other older transmission measurements⁸ as well as with the more recent measurements by Dilg et al.⁹ They do not agree with the evaluations of either Horsley and Stewart,⁶ of Seagrave⁵; both of which are basically extrapolations from higher energy data, and appear to be significantly too low. The more recent Seagrave⁵ evaluation, which gives $\sigma_{\text{free}} = 3.15$ barns, is also based on an analysis by van Oers and Seagrave¹⁰ of spin coherent, and spin incoherent

cross-section measurements by Gissler,¹¹ and by Bartolini et al.,¹² respectively. Their analysis yields scattering lengths of $^2a = 0.15 \pm 0.05_{\text{fm}}$ and $^4a = 6.13 \pm 0.03_{\text{fm}}$. The analysis also uses phase shifts from higher energy angular distribution data.

The present results, and the calculation by Harms and Laroze,² tend to confirm the quartet scattering length, $^4a = 6.35 \pm 0.02_{\text{fm}}$ which was obtained by Dilg et al.,⁹ and are in basic agreement with theoretical expectations.^{1,13} The present results do not specify 2a because of its very small contribution to the cross section. However, the agreement with Dilg et al.⁹ with respect to σ_{free} and 4a lends confidence to their value of $^2a = 0.65 \pm 0.04_{\text{fm}}$,¹⁴ which is theoretically preferred over the smaller value.

Incidentally, the phase shift analysis of van Oers and Seagrave¹⁰ does not contradict the present results because of the large experimental errors in their quoted phase shifts. In fact, an extrapolation of their quartet values of $k \cot \delta$ down to zero energy actually appears to prefer the Dilg et al.⁹ value of $^4a = 6.35_{\text{fm}}$ over the alternate value of 6.13_{fm} which they used. In addition, due to the large errors in the doublet phase shifts, their analysis appears to be as consistent with $^2a = 0.65_{\text{fm}}$ as with the alternate value of $^2a = 0.15_{\text{fm}}$, which they used.

We conclude that the results of the present experiment are in basic agreement with the theoretical expectations, and tend to confirm the results of the thermal measurements of Dilg et al.

Acknowledgments

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FIGURE CAPTIONS

Fig. 1 The Observed Neutron Spectrum with 8 Inches of Iron Placed between the Neutron Source and the Detector. Cross sections were evaluated at energies corresponding to a few selected peaks in the neutron flux. These peaks are identified by the energies (in keV) marked directly above them — continuum cross sections were normalized to these cross sections at the energies corresponding to these peaks.

Fig. 2 Total Neutron Cross Sections of Deuterium from Zero to 1000 keV. The solid circles, ($\bullet$), are the results of the iron filter experiment. The solid squares, ($\blacksquare$), are obtained from Clement et al.⁴ The vertical lines are the results of the continuous energy experiment as discussed in the text. The open circle, ($\circ$), and the solid triangle, ($\blacktriangle$), at zero energy represent the thermal cross section of Fermi and Marshall,⁷ and Dilg et al.⁹ respectively. The open diamond, ($\diamond$), is the thermal cross section deduced from the works of Gissler¹¹ and of Bartolini et al.¹² The hatched curve, below 300 keV is excerpted from the evaluation by Seagrave.⁵ The solid curve is due to the theoretical calculation by Harms and Laroze.² The errors shown reflect statistical uncertainties only.

Figure 1

Figure 2

TOTAL NEUTRON CROSS SECTIONS OF ^3He
IN THE ENERGY RANGE 0.7 TO 30 MEV

C. A. Goulding,* P. Stoler and J. D. Seagrave#

The total neutron cross section of ^3He was measured using a gaseous sample obtained from Los Alamos Scientific Laboratory (LASL). The gas was contained in a stainless steel chamber with thin end windows. The description of the experimental technique is identical to that reported in the previous progress report.¹

Three separate runs were taken with different neutron intensities and burst widths. This was done in order to insure maximum statistical accuracy and resolution over the entire energy range, since the cross section (and hence transmission) vary by almost an order of magnitude from 1 to 30 MeV. Agreement between the three runs was within 1% over most of the energy range covered, which lends confidence in the accuracy of the results. In addition, considering our experience in similar previous experiments, we feel that the cross sections are accurate to within $\pm 1\%$ (standard deviation) over most of the energy range.

The experimental results are shown in Figs. 1, 2 and 3. They appear to be smooth over the entire energy range, except for the well-known broad peak at around 3 MeV. In particular, there is no sign of the sharp anomaly around 3.08 MeV (outside our statistical errors of about $\pm 1\%$ and resolution of about 8 keV), which has previously been reported in polarization experiments.²

Further analysis is proceeding, and it is hoped to resolve the discrepancy between elastic scattering at 23.7 MeV, and the extrapolation of previously measured total cross sections at 21 MeV.

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FIGURE CAPTIONS

- Figs. 1 and 2 The First Two Runs Combined and Averaged to
20 nsec. The +'s are LASL results.
- Fig. 3 The Results of the Third Run Averaged to 50 nsec.

Figure 1

Figure 2

Figure 3

FISSION NEUTRON MULTIPLICITY MEASUREMENTS

R. L. Reed,* R. W. Hockenbury and R. C. Block

The $\bar{\nu}$ measurements for ^{235}U and ^{233}U using the improved detector system^{1,2} have been completed. The amounts of linac time used for various neutron energy regions are shown in Table 1 with some of the machine conditions.

The data from the detection system are stored in the PDP-7 computer as detected neutron multiplicities in time-of-flight channels determined by when the fission events occurred following linac pulses. A variable time compression point is used to increase the total time-of-flight that can be covered with a single run. Nubar values are calculated for each of the 290 time-of-flight channels.

The nubar value for a particular neutron energy region is then determined by averaging the nubar values over the time-of-flight channels comprising that region. In general the resonance regions are chosen to be isolated from neighboring resonances. The thermal region is divided into consecutive sets of channels corresponding to equal time-of-flight increments on the order of 1-2 milliseconds. It is the region averaged values that are plotted in Figs. 1-4. One will note that the points plotted show the region over which they were determined by a horizontal line equal to the time-of-flight region width through the plotted point. The statistical errors (standard deviations) on the plotted values are shown by the vertical lines through the point. The nubar values plotted have not been corrected for detector efficiency. The average lines plotted in each resonance region figure are the averages of all the time-of-flight points. Those in the thermal region figures are the averages only over the thermal regions.

Table 2 gives some observations about Fig. 1-4. Note that these figures do not represent all the data for those energy re-

*Based in part on the Ph.D. Thesis of R. L. Reed.

gions. The errors and relative deviations given for the thermal data refer only to that portion of the time-of-flight data below 0.2 eV.

We have yet to perform all the statistical tests necessary to determine any correlations of nubar and various nuclear parameters, but some preliminary conclusions are possible from the results of Figs. 1-4. In both isotopes, nubar appears to be constant to 0.1% over the thermal region. For the ^{235}U data, this contradicts previous results which showed a 0.6% change (or slope) in nubar over the thermal region.^{3,4,5,6} In general, for these partial results the resonance nubar values do not vary by more than 1% for ^{235}U and 1.5% for ^{233}U .

The 1.4 gram ^{239}Pu multiplate fission chamber has been borrowed from the Oak Ridge National Laboratory to carry out measurements in an attempt to resolve discrepancies in reported nubar results of several investigators for ^{239}Pu .^{6,7,8} Using the improved detection system and a more efficient data acquisition program in the PDP-7 computer, the data will be accumulated at a rate nearly four times that done previously.⁴

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FIGURE CAPTIONS

- Fig. 1 Nubar Values for Selected Resonances in the Low Energy Resonance Region of ^{235}U .
- Fig. 2 Nubar Values Over the Thermal Region and Some Nearby Resonances of ^{235}U .
- Fig. 3 Nubar Values for Resonances in the Low Energy (5-40 eV) Resonance Region of ^{233}U .
- Fig. 4 Nubar Values for the Thermal Region and Adjacent Resonances of ^{233}U .

U235 RESONANCE NUBAR 416-426

Figure 1

Figure 2

Figure 3

Figure 4

Table 1. Linac Time and Conditions for the ^{233}U and ^{235}U Measurements

Set	Sample	T-O-F Delay	Region (energies spanned)	Linac Time	Pulse Width	Rep. Rate
1	^{235}U	349 μsec	Resonance (5-28 eV)	165 hours	.25 μsec	300 pps
2	^{235}U	549 μsec	Thermal (.008-10 eV)	60 hours	.25 μsec	33 pps
3	^{233}U	289 μsec	Resonance (5-40 eV)	200 hours	.25 μsec	300 pps
4	^{233}U	520 μsec	Thermal (.008-10 eV)	72 hours	.25 μsec	30 pps
5	^{233}U	172 μsec	Resonance (20-100 eV)	40 hours	.25 μsec	300 pps

Table 2. Observations and Other Information on Partial Results Shown in Figures 1-4^{a,d}

Set	Sample	Linac Time	Region	Compression Point	Error Range Standard Deviation	Maximum Deviation from Average ^b	Maximum Region to Region Difference
1	^{235}U	40 hrs.	Resonance (5-28 eV)	201	0.1% -0.5%	1%	1.8%
2	^{235}U	30 hrs.	Thermal (.008-10 eV)	151	0.12%-0.2%	0.25%	0.5%
3	^{233}U	55 hrs.	Resonance (5-40 eV)	181	0.1% -0.8%	1%(2%) ^c	2.2%(3%) ^c
4	^{233}U	30 hrs.	Thermal (.008-10 eV)	151	0.15%-0.3%	0.15%	0.3%

a For Figures 2 and 4, the quoted errors and relative differences refer only to the thermal region, below 0.2 eV.

b Average is entire time-of-flight average for resonance data figures. Average is only for thermal region in thermal data figures.

c The value in parentheses must be accepted if the 31.2 eV resonance region nubar value is included.

d These observations are approximate and only for the partial data shown in Figures 1-4. They are not to be accepted as final conclusions.

KEV NEUTRON ELASTIC SCATTERING CROSS SECTION IN IRON

R. Zuhr,* Z. Bell and K. Min

During this year we have continued our study of the differential elastic scattering cross section of natural iron. Time-of-flight measurements were made at six angles from 45 to 150 degrees in the energy region from 5 to 600 keV. Details of the experimental apparatus have been given in previous reports.^{1,2}

A Monte Carlo computer code for evaluating the effects of multiple scattering has been completed. This code, which is based on the work of Lane and Miller,³ is intended for use on the CDC-6600. It utilizes energy-dependent cross sections and includes multiple scattering through fourth order. The scattering corrections from this program were applied to our earlier data,¹ resulting in corrected differential scattering cross sections from 10 to 600 keV that were presented at the Washington Meeting of the American Physical Society.⁴

In order to improve the accuracy of our measurements, which were made relative to a lead standard, the problem of absolute cross-section measurements has been investigated. Stability of detector sensitivity with position appears to be adequate and the shape of the neutron spectrum was shown to be constant for changes in linac energy larger than those encountered in normal operation.⁵ At this time, however, an adequate method of monitoring the flux is not available.

Major changes in the experiment, which were suggested earlier to improve counting rate and thus statistical accuracy, have recently been incorporated. Data on iron and nickel were taken using dual detectors, revised target geometry, and improved collimation.

The resulting time-of-flight spectrum is presented in Fig. 1 and shows an order of magnitude increase in counting rate over

*Based in part on the Ph.D. Thesis of R. Zuhr.

earlier runs. These data are currently being evaluated and it is anticipated that a marked improvement in the accuracy of the differential cross sections will result.

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FIGURE CAPTION

Fig. 1 Time-of-flight Spectrum for Iron at 150° , 1/32 nsec/channel. This run was taken with revised collimation and sample geometry.

Figure 1

DOPPLER EFFECT AND RESONANCE SELF-SHIELDING STUDY ON DEPLETED-URANIUM IN THE UNRESOLVED REGION

T. Y. Byoun,^{*} T. Semler[‡] and R. C. Block

Most of the results of the average transmission and self-indication ratio measurements have been described in the previous report¹ and presented at the National ANS Topical Meeting at Kiamesha Lake in September 1972.²

It will be useful to summarize briefly the previous results. The analysis of the temperature-dependent average transmission by using the stochastic sampling method was discussed in the neutron energy from 5.0 keV to 5.6 keV. The analytical calculation of the data was introduced and results of this approach were compared with the experimental results.

In this report, some more detailed results and analysis will be discussed. Average total cross sections, $\langle\sigma_t\rangle$, in the neutron energy from 1 keV to 100 keV have been determined by using the least squares method from five sets of the room temperature average transmission data. The exponential term in the expression of the average transmission, $\langle TR \rangle$, was approximated to four terms as follows:

$$\langle TR \rangle_i = e^{-n_i \langle \sigma_t \rangle} \left\{ 1 + \frac{1}{2} n_i^2 \langle (\sigma_t - \langle \sigma_t \rangle)^2 \rangle - \frac{1}{6} n_i^3 \langle (\sigma_t - \langle \sigma_t \rangle)^3 \rangle \right\} \quad (1)$$

where $\langle \dots \rangle$ stands for average over energy interval, ΔE , and n_i is sample thickness in the units of atom/barn. For a selected reasonable value of average total cross section, $\langle \sigma_t \rangle$, the calculated average transmissions, $\langle TR \rangle_i^{cal}$ were compared with the experimental average transmission, $\langle TR \rangle_i^{exp}$ by using the following chi-square value, Q ,:

$$Q = \sum_i w_i [\langle TR \rangle_i^{cal} - \langle TR \rangle_i^{exp}]^2 \quad (2)$$

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$$Q \approx Q_0 + \left(\frac{\partial Q}{\partial a} \right)_0 da + \frac{1}{2} \left(\frac{\partial^2 Q}{\partial a^2} \right)_0 (da)^2 \quad (2)'$$

$$\delta_{\langle \sigma_t \rangle} \equiv da = \frac{-(\partial Q / \partial a) \pm \sqrt{(\partial Q / \partial a)^2 - 2(\partial^2 Q / \partial a^2)(Q_0 - Q)}}{(\partial^2 Q / \partial a^2)_0} \quad (3)$$

where w_i = inverse of the square of the standard deviation of the experimental transmission $1/[\delta_{\langle TR \rangle_i}]^2$,

$\delta_{\langle \sigma_t \rangle}$ = increment of the average total cross section for a next step of the iteration procedure.

This procedure was repeated selecting new values of $\langle \sigma_t \rangle$ by using Eq. (3) until Q in Eq. (2) was minimized.

The average cross sections in the neutron energy from 1 to 100 keV obtained by the above method are compared with the theoretical calculation in Fig. 1. The formula used in this theoretical calculation was the following:

$$\langle \sigma_t \rangle = 2\pi^2 \lambda_1 \lambda_2 \sum_{l=0}^{\infty} (2l+1) v_l S_l \cos 2\xi_l + \sigma_p \quad (4)$$

, where

λ = wave length

v_l = hard sphere penetration factor for angular momentum, l ,

ξ_l = potential scattering phase shift for angular momentum, l

σ_p = potential scattering cross section

The strength functions for s- and p-wave and potential cross section used in this calculation are listed in Fig. 1. As we can see in Fig. 1, the overall fit of the average total cross section is in good agreement with the experimental values. However, considering local fluctuations of the average cross sections, it would be better to use local values of average resonance parameters in different energy regions. Figure 1 shows that the s-wave contribution of the total cross section dominates in the energy range below 6 keV and the p-wave contribution is comparable with s-wave contribution in the energy range 20-30 keV.

In Fig. 2 the temperature dependence of the total cross section variance is shown in the energy range from 10 to 100 keV. The average resonance parameters used in this calculation were those reported in Ref. 2. As we can see in Fig. 2, the variance of the total cross section, $\langle(\sigma_t - \langle\sigma_t\rangle)^2\rangle$, is decreasing as the neutron energy and the temperature of the uranium sample increase. These effects were expected since, as temperature increases, the Doppler broadening of the cross section increases, resulting in smoother cross sections. Similarly, at the higher energy region where the resonances are highly overlapped, smoother cross sections should be expected than in the lower energy region. This smoother cross section causes the lower variance of the total cross sections.

In Figs. 3 and 4, the results of the analytical calculation² are compared with experimental values for both average transmission and average self-indication ratio measurements respectively. Figures 3 and 4 show that the agreement of the analytical calculation is very good for thin samples. However, as mentioned in previous reports^{1,2} for thicker samples and for lower energy region, the agreement becomes poorer, since, for large values of $n_1\sigma_t$ the four-term expansion approximation is not valid.

At this moment we are interested in comparison of our average resonance parameters obtained from the analytical approach with those of ENDF/B-III in the unresolved resonance region of ^{238}U .

The analysis of the low energy data (in the resolved resonance region) is also being pursued by using the Harvey-Atta code³ and a Monte Carlo code⁴ (both ideal gas models) for the different temperature data.

Differences among various models of Doppler broadening will be examined; i.e., the ideal gas model, Lamb's effective temperature model^{5,6} and Egelstaff and Holt's model^{6,7}, etc. However, we expect some difficulty in analyzing low energy data because of the poor counting statistics, the existence of the significant resonance-to-resonance interference, and the broad timing resolution.

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FIGURE CAPTIONS

- Fig. 1 Average Total Cross Sections of Depleted-Uranium.
- Fig. 2 Temperature and Energy Dependence of the Variance of Total Cross Sections.
- Fig. 3 Average Transmission of Depleted-Uranium at Room Temperature.
- Fig. 4 Average Self-Indication Ratio of Depleted-Uranium at Room Temperature.

Figure 1

Figure 2

Figure 3

Figure 4

EXPERIMENTAL RESOLUTION FUNCTION THEORETICAL EVALUATION

K. Alfieri* and P. J. Turinsky

To reduce TØF transmission spectra to total neutron cross section versus energy dependence, the experimental resolution function must be evaluated. The connection between count rate in TØF channel n and total cross section, $\Sigma_t(E)$, for a sample of thickness d is given via the resolution function, $R_n(E')$, by

$$C_n(d) = \int_0^{\infty} R_n(E') e^{-\Sigma_t(E')d} dE'.$$

With multi-level effects becoming more prominent in our experiments, one must resort to a shape analysis of the transmission spectra,

$$T_n(d_1, d_2) = \frac{C_n(d_1)}{C_n(d_2)} \quad \text{where } d_1 > d_2$$

to obtain a multi-level resonance parameter set. Hence a knowledge of $R_n(E')$ is required and cannot be eliminated for multi-level cross-section construction as via the area function analysis approach to single-level cross-section construction for well isolated resonances.

As reported elsewhere,¹ our keV through low MeV transmission measurements require neutron spectrum softening of the evaporation spectrum from the tantalum electron-neutron conversion target, which is achieved by a $(-CH_2-)$ moderator. Hence the primary resolution broadening effects are caused by the electron pulse width and at lower energies also by the $(-CH_2-)$ moderator. In our calculation of the resolution function, we have treated the time-dependent neutron moderation problem by the leakage probability approach.² The electron pulse shape was approximated by a ramp on-off function with a 10 nsec ramp and half-width Δt_e . TØF sorting for the n^{th} channel was represented by a square wave of

*Based in part on the Master's Engineering Project of K. Alfieri.

duration Δt initiated at time t_n . These assumptions imply that the resolution function for a flight path of distance X can be approximated by

$$R_n(E') = \epsilon(E') R_n^O(E') .$$

Here $\epsilon(E')$ is a slowly varying function related to detector efficiency and $R_n^O(E')$ is given by

$$R_n^O(E') = \int_{t_n}^{t_n + \Delta t} \langle L_t(E', t' - \frac{X}{v}, \Delta t_e) \rangle dt'$$

where $\langle L_t \rangle$ denotes the leakage spectra from the $(-CH_2-)$ moderator calculated by the leakage probability approach for an electron pulse of half-width Δt_e . Figure 1 illustrates $R_n^O(E')$ as calculated for conditions corresponding to our iron minima experiment ($\Delta t_e = 50$ nsec, $\Delta t = (1/32)$ μ sec and $X = 27.89$ m). In Figure 1, E_n just denotes the value of E' at which $R_n^O(E')$ is maximized. These results have been employed in the analysis of the iron minima measurement. Experimental verification of the accuracy of the calculated experimental resolution function is planned, since from our iron experiment some doubt has risen as to the accuracy to which we can calculate tail effects of the resolution function.

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FIGURE CAPTION

Fig. 1 Calculated Ideal Normalized Resolution Function, $R_n^O(E')$, for Three Different Channels.

Figure 1

STRENGTH FUNCTION FITS USING PARTIAL WAVE DEPENDENT
OPTICAL MODEL PARAMETERS

J. Sierra* and P. J. Turinsky

Previously¹ it has been pointed out the unlikelihood of fitting simultaneously the potential scattering radius R' , s-wave strength function S_0 and p-wave strength function S_1 using the optical model for partial wave (ℓ) independent parameters. This difficulty was encountered when attempting to fit the deep experimentally observed² minima in S_1 about mass 60 and 160. We have therefore repeated the fitting process, using partial wave dependent parameters and in this manner obtain quite satisfactory fits.

To minimize the number of free optical model parameters which are now allowed to have ℓ dependence, we have been guided by approximate theoretically based formulations. These results suggest that the dominant ℓ dependence of the optical potential is perhaps contained in the surface imaginary term. Allowing therefore only ℓ dependence in the strength of the imaginary term, thereby reducing the number of free parameters considerably, we employ the optical potential

$$V^{(\ell)}(r) = -V_{rs} \cdot f(a_{re}, R, r) - i \cdot 4W^{(\ell)} g(a_{Im}, R, d, r) \\ - V_{S0} \cdot (\vec{\sigma} \cdot \vec{r}) \cdot \kappa^2 \cdot \frac{h(a_{S0}, R, r)}{r}$$

where

$$f(A, R, r) = \frac{1}{1 + e^{\left(\frac{r-R}{a}\right)}}$$

$$g(a_{Im}, R, d, r) = \left| \frac{d}{dr} f(a_{Im}, R+d, r) \right|$$

*Based in part on the Master's Thesis of J. Sierra.

$$h(a_{S_0}, R, r) = \left| \frac{d}{dr} f(a_{S_0}, R, r) \right|$$

and the effective nuclear radius is given for mass number A by

$$R = r_0 A^{1/3}$$

Hence, a total of nine free parameters must be determined for $\ell=0$ and 1, in contrast to the usual seven. The employed potential is also identical in radial form to the normal optical potential with the exception of the imaginary term which allows shifted radial dependence with respect to the nuclear surface.

This potential was employed in a modified version of the ABACUS optical model code. By assigning the optical parameters the values given in Table 1, the successful simultaneous fits to R' , S_0 and S_1 shown in Figs. 1-3 were obtained. The curves labeled "desirable fit" represent a smooth visual fit through considerable experimental data collected at various neutron energies. Our calculations were therefore performed at 30 keV, 100 and 300 keV, illustrating the sensitivity near maxima of S_0 and S_1 to neutron energy due to single-particle binding.

We hence conclude that the partial-wave dependent optical potential that has been used is capable of adequately fitting S_0 , S_1 and R' simultaneously. With however nine free parameters, the form employed and parameter set uniqueness are subject to question. Theoretical work is underway to clarify this point; for example, is there any theoretical foundation to expect $W^{(0)}/W^{(1)}$ to be approximately four as observed?

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FIGURE CAPTIONS

- Fig. 1 P-wave Neutron Strength Function vs. Atomic Mass Number.
 Fig. 2 S-wave Neutron Strength Function vs. Atomic Mass Number.
 Fig. 3 Potential Scattering Radius vs. Atomic Mass Number.

Figure 1

Figure 2

Figure 3

Table 1

Partial Wave Dependent Optical Model Parameter Set Employed
(Units: Potential-MeV. , Length-fm.)

$$V_{re} = 47. \quad , \quad a_{re} = 0.51$$

$$W^{(\ell=0)} = 12. \quad , \quad a_{Im} = 0.23 \quad , \quad d = 0.30$$

$$W^{(\ell=1)} = 3. \quad , \quad a_{S0} = 0.37$$

$$V_{S0} = 6. \quad , \quad r_0 = 1.29$$

CORRELATIONS BETWEEN NEUTRON AND RADIATIVE WIDTHS

M. Lubert,^{*} R. C. Block and N. C. Francis[†]

The cross sections for the chromium isotopes measured at the RPI LINAC indicate a positive correlation between the measured neutron and radiation widths.¹ The radiation widths are normally expected to be distributed as a Chi-square distribution with n degrees of freedom ($n \sim 50$). The radiation widths are usually constant over the energy range of interest. It has been shown^{1,2} that the radiation width is a function of both the compound nucleus and channel reactions. The channel reactions, at low energies, preferentially select those states which have a large single-particle character. An s-wave neutron is coupled to the core of the target nucleus and undergoes an E1 gamma-ray transition to a low-lying single-particle p-state without forming a compound nucleus. This effect is strongest for those final states which have strong single-particle components in their wave functions. The channel contribution exhibits resonance energy dependence. The correlations between the partial radiative width and the neutron reduced width are expected for those cases where the (d,p) spectroscopic factors are large. Calculations have been performed in an attempt to understand the correlation observed in the RPI experiments. The initial work examined the channel contributions for the compound nuclei ^{57}Fe , ^{53}Cr and ^{61}Ni . These nuclei have strong (d,p) strengths with low-lying p-states. The information available in stripping, (n, γ), (γ ,n), and gamma-ray spectra for thermal and resonant neutrons was examined.

The photoneutron cross sections for ^{57}Fe and ^{53}Cr were measured by Baglan³ and Jackson.⁴

 ^{57}Fe

The ^{57}Fe (γ ,n) cross section was calculated, using both the channel direct and the compound nucleus reaction amplitudes. The

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R-matrix phase shifts are given by the following equations:

$$R = \left\{ \sum_{\lambda} \frac{\gamma_{\lambda}^2}{E_{\lambda} - E} + R^{\infty} \right\}$$

$$\delta = \tan^{-1} RP - kR_0$$

To obtain the channel contribution, it is necessary to calculate the final state continuum s-state wave function. The required phase shift is calculated using R-matrix theory where γ_{λ}^2 is the reduced width, R^{∞} the contribution from non-explicit levels, P the penetrability, k the neutron wave number in the center-of-mass system and R the nuclear radius. The $^{57}\text{Fe}(\gamma, n)$ cross section was evaluated using the ^{56}Fe resonance parameters presented in BNL-325.

Baglan reports a non-resonance cross section of 0.052 mb at 26 keV (neutron energy) for $^{57}\text{Fe}(\gamma, n)$. The theoretical value was normalized to this experimental point resulting in a reduced width factor of 0.22. This reduced width was then used in calculating the thermal capture cross section for ^{56}Fe and the channel ground-state partial radiative widths for $^{57}\text{Fe}(\gamma, n)$. The thermal $^{56}\text{Fe}(n, \gamma)$, from detailed balance was 0.22 b. The experimental value, assuming a ground-state transition fraction of 0.25⁵ is 0.67 b. Consequently, the compound nucleus contribution cannot be neglected in calculating the thermal capture. The bulk of the thermal capture cross section comes from the bound level at -4.39 keV.⁶ The 28 keV level contributes only 0.057 b which is about a factor of four smaller than the channel contribution. The channel partial radiative widths for transitions to the ground state, obtained from area analysis of Baglan's data are shown in Table 1. The results of the analysis are interesting from several viewpoints. First, the theoretical calculation predicts a level at 80 keV with $\Gamma_{\gamma 0} = 0.14$ eV (not listed in Table 1). This level is not observed in the experiments. Secondly, the theoretical line shapes are asymmetric. It is expected that levels with large channel components would exhibit a marked asymmetry. The shapes computed for single levels show constructive interference on the

low (neutron) energy side of the resonance and destructive interference above the resonance. The level-level interference introduced by the R-matrix further distorts this line shape. The experimental cross sections do not in general look markedly asymmetric nor does the cross section appear to go through a minimum above the resonance as predicted by the theory. This can be attributed to two effects; namely, experimental resolution broadening and the contribution due to compound nucleus resonance amplitude. The interference between the channel and compound nucleus amplitudes affects the line shape. Further, it is possible that a level would not appear in the experimental results if the amplitudes cancelled. It can be shown that the partial ground-state radiative width is given by

$$\Gamma_{\gamma 0} = \Gamma_{\gamma 0}^{\text{channel}} + \gamma_0^{2\text{cpd}} \pm 2\sqrt{\Gamma_{\gamma 0}^{\text{channel}}} \sqrt{\gamma_0^{2\text{cpd}}} \quad (1)$$

Assuming the calculated channel contribution to be reasonable, the compound nucleus contribution to the partial radiation width can be estimated. The average compound nucleus reduced width amplitude for the ground-state was found in this way to be 0.197.

The experimentally determined radiation widths were compared to a Porter-Thomas distribution. Although the number of levels is small, a $\chi^2 = 11.26$ was obtained for ^{57}Fe . This indicates that for $\nu = 1$ the measured widths obey a Porter-Thomas distribution with probability $P < 0.02$. The compound nucleus radiative widths computed with Eq. (1) yielded a $\chi^2 = 0.67$ which indicates that the Porter-Thomas distribution is satisfied with probability $0.5 \leq P \leq 0.7$. The reduced width factor was varied from 0.05 to 1.0. The χ^2 changed from 1.04 to 12.2. Although the values of χ^2 changed slowly so that a reduced width factor of 0.6 still fitted a Porter-Thomas distribution with probability $0.1 \leq P \leq 0.3$, the distribution in sign was almost totally one-sided. The 'best' reduced width-factor should provide a minimum χ^2 and the most random sign for the compound nucleus amplitude. The correlation co-

efficient between Γ_n^0 and $\Gamma_{\gamma 0}$ obtained from the experimental data showed minimal correlation. In the theoretical analysis in which the channel contribution is major, a strong correlation is obviously obtained.

An estimate of the total capture channel radiative width including excited states can be obtained from the (d,p) strength data.⁵ This results in a factor of 4.6 which multiplies the ground-state channel contributions given in Table 1.

The significant results obtained from the examination of ^{57}Fe are: first, the analysis of the experiments must include level-level effects; and second, that compound nucleus and channel interference can be of considerable importance when the channel contribution is large.

^{53}Cr

The (γ, n) cross section for ^{53}Cr was calculated using R-matrix phase shifts. The experiments of Baglan and Jackson again provide the experimental data for the analysis. The results obtained by Baglan include many excited states, whereas Jackson predominately measured ground-state transitions. Baglan does not observe the peak at 113 keV which should have been resolved. In view of this, he assigned a value of $\Gamma_{\gamma 0} = 0$ for this resonance. The levels at 93.5, 138.0 and 460.5 keV have large total widths and are assumed spread out in the background. Jackson does report partial radiation widths for the 92 and 117 keV lines. The experimental 92 keV peak in Baglan's results which is spread in the background was used to obtain an estimate of the reduced width factor. The resultant reduced width factor obtained from fitting the theoretical to experimental cross section was 0.5. Although Jackson did not report cross section versus energy, the 92 keV line appeared asymmetric. A calibration of energy-versus-channel was constructed from Jackson's curve and the non-resonance tail on the low-energy side of the resonance plotted as a function of energy. The theoretical and experimental shapes were in good

agreement. This reduced width factor was used in calculating the compound nucleus reduced width amplitudes from Eq. (1) and shown in Table 2. The χ^2 test for $\theta^2=0.5$ show that the compound nucleus widths obey a Porter-Thomas distribution within the ten per cent confidence limit.

^{61}Ni

The (γ, n) cross section for ^{61}Ni was calculated using R-matrix phase shifts. The $\Gamma_{\gamma 0}$'s for each level were again obtained from an area analysis. An attempt was made to determine the reduced width by fitting the 11.6 keV resonance reported by Jackson. Unfortunately, the uncertainty in background level prevented shape fitting the experimental curve below the resonance. In order to estimate the reduced width factor, the compound nucleus partial radiation widths were calculated for a series of reduced width factors. The χ^2 values were relatively constant for $0.1 < \theta_0^2 < 0.5$. The criteria of minimum χ^2 and random distribution of sign are best satisfied by $\theta_0^2=0.1$. This is easily uncertain to a factor of two. The experimental and theoretical values for the partial radiative widths are summarized in Table 3.

The calculated thermal (n, γ) cross section for ^{60}Ni was 0.83 b. The experimental value of 1.16 b was computed assuming the transition rate to the ground-state is 0.41^5 . The channel contribution is significant. The energy dependent ^{60}Ni (n, γ) cross section was obtained from detailed balance, and it shows a cross section of 5-6 mb in the energy range $1 \text{ keV} < E < 10 \text{ keV}$. The (d, p) strength to these same final states indicate that the excited state transitions will increase the (n, γ) cross sections by a factor of two. This yields a calculated (n, γ) cross section of approximately 10-20 mb for $1 \text{ keV} < E < 10 \text{ keV}$. The cross section measured at RPI showed a substantial cross section of the order of 50 mb. The channel contribution appears to be significant for this cross section.

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Table 1

Partial Radiative Widths for $^{57}\text{Fe}(\gamma, n)$

$E_n(\text{keV})^3$	$E_n(\text{keV})^4$	$\Gamma_{\gamma 0}(\text{eV})^3$	$\Gamma_{\gamma 0}(\text{eV})^4$	$\Gamma_{\gamma 0}^{\text{cal'd}}$
26.0	26.9	0.17	0.112	0.275
69.1	70.2	0.24	0.082	0.074
124.0	125.1	0.056	0.105	0.074
135.0	136.0	0.072	0.068	0.21
162.0	163.0	0.12	0.066	.089
179.0	181.0	0.42	0.423	0.30
212.0	212.0	0.72	0.683	1.03
232.0		0.52		0.089
259.0		0.22		0.27
299.0		0.64		0.45

Table 2

Partial Radiative Widths for $^{53}\text{Cr}(\gamma, n)$

$E_n(\text{keV})^3$	$\Gamma_{\gamma 0}(\text{eV})^3$	$\Gamma_{\gamma 0}(\text{eV})^4$	$\Gamma_{\gamma 0}(\text{eV})^{\text{cal'd}}$	$\Gamma_{\gamma 0}(\text{eV})^{\text{cpd}}$
50.2	0.17		0.90	0.287
141.0	0.80		2.70	0.561
239.0	1.60		0.33	0.477
285.0	0.72		0.20	0.161
331.0	3.00		0.87	0.639
369.0	1.30		1.98	0.071
406.0	0.36		4.17	2.079
420.0	0.24		0.19	0.003
535.0	0.76		2.12	0.341
97.1		1.275	2.34	0.160
123.2		0.93	0.47	0.078

Table 3

Partial Radiative Widths for $^{61}\text{Ni}(\gamma, n)$

$E_n(\text{keV})^4$	$\Gamma_{\gamma 0}(\text{eV})^4$	$\Gamma_{\gamma 0}(\text{eV})^{\text{cal'd}}$	$\Gamma_{\gamma 0}(\text{eV})^{\text{cpd}}$
12.4	0.367	0.501	0.011
43.1	0.018	0.017	
98.6	0.102	0.066	0.004
106.8	0.209	0.066	0.040
160.8	0.166	0.167	
186.2	0.062	0.213	0.045
197.0	0.557	0.215	0.080

DEPARTURES FROM STATISTICAL CROSS-SECTION BEHAVIOR EXAMPLE:
 $n + {}^{40}\text{Ca}$ S-WAVE ELASTIC SCATTERING

P. J. Turinsky

There is experimental evidence of anomalous broad resonance structure superimposed on fine structure in the total neutron cross section of ${}^{60}\text{Ni}$, ${}^{140}\text{Ca}$ and other isotopes. It is tempting to interpret such structure as intermediate structure, perhaps doorway states. Such an interpretation based exclusively on graphical interpretation of the data can however be erroneous for the following reasons. First, several reaction channels may be involved when displaying the total cross section; whereas, intermediate structure refers to a particular channel. Secondly, the tail of the Porter-Thomas distribution for reduced neutron widths implies that broad resonance structure is possible without attributing it to intermediate structure. Since anomalous cross-section behavior requires the use of possible strongly energy dependent average resonance reduced widths in present statistically based treatments of the unresolved resonance region for multi-group constant generation calculations, we have developed a method for quantifying how likely is an observed anomalous broad resonance structure within the normal statistical framework.

As reported previously,³ a computer code has been written which calculates how often a structure observed in the energy averaged cross section for a given reaction channel with particular identifying properties would occur, assuming normal statistical behavior. The identifying properties of the structure are its width, number of contributing resonances and magnitude for a specified energy averaging interval. The energy averaged cross section for a given channel is constructed via a reduced R-matrix multi-level formalism by sampling the Porter-Thomas distribution for the reduced neutron width and the Wigner distribution for the level spacing in such a way that the average reduced neutron width and level spacing are preserved for a specified energy interval.

This computer code has been employed to study the broad resonances found in the energy averaged s-wave neutron elastic scatter-

ing cross section below 1.1 MeV of ^{40}Ca . Using the s-wave resonance parameters of Ref. 4, the energy averaged cross section for the $\frac{1}{2}^+$ elastic scattering channel of ^{40}Ca is shown in Fig. 1 for energy averaging intervals of 150 keV and 300 keV, respectively 3 and 6 times the $\frac{1}{2}^+$ level spacing. Broad structure at 300, 625 and 950 keV is obvious. To quantify how frequently such fluctuations occur under normal statistical behavior, our Monte Carlo computer code was employed, where Fig. 1 also shows the ensemble averaged energy averaged $\frac{1}{2}^+$ channel cross section we thus calculated. We found for an energy averaging interval of 150 keV, fluctuations characterized by the width and magnitude of the 300 keV fluctuation occurs every 2 MeV; whereas, fluctuations such as at 625 keV and 950 keV occur every 3 MeV. Hence the observed fluctuations are not highly unlikely if only characterized by width and magnitude. If we further characterize the fluctuations contained in each structure in addition to width and magnitude by the number of contributing resonance levels, we obtain spacings of about 5.4, 4.6 and 9.4 MeV for the resonances such as those at 300, 625 and 950 keV respectively. Most important, even though we have not performed the explicit probabilistic calculations, from the just stated spacings we conclude it is unlikely that three such fluctuations as observed in the 1.1 MeV interval could occur simultaneously unless nonstatistical behavior enters.

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FIGURE CAPTION

Fig. 1 Energy Averaged Neutron Cross Section for the $\frac{1}{2}^+$ Elastic Scattering Channel of ^{40}Ca .

Figure 1

REACTOR PHYSICS AND ENGINEERING - EXPERIMENTAL

REACTOR PHYSICS AND ENGINEERING - EXPERIMENTAL

During the past year, this program reached the stage where definitive checks of differential neutron cross-section data, based on the analysis and interpretation of clean integral experiments on bulk homogeneous media, began to yield results, leading to comprehensive journal publications and fruitful interactions with other data evaluation groups and cross-section measurement programs. A full-fledged paper¹ on the experimental and analytical studies of fast neutron transport in bulk iron was published during the year in Nuclear Science and Engineering. This paper represented the first major phase of the test of principal available data files and fast neutron calculational methods for iron, providing important conclusions and recommendations regarding preferred data and the emphasis in future differential measurements and evaluations. Some of the conclusions of our studies based on integral measurements and analysis for iron helped to focus attention, among other things, on the cross-section minima and the role of impurities and have prompted new measurements^{2,3,4} by cross-section measurers. This is offered here as an example of the importance of such clean integral experiments in providing checks of differential cross-section data.

The analysis of fast neutron angular flux spectrum data on iron is continuing — especially with respect to the newly issued (revised) data files and sophistications in the transport analytical model (such as incorporating specific anisotropic scattering effects, affecting high-energy data). A paper⁵ relating to some of these additional results was recently presented at the Fourth International Conference on Reactor Shielding in Paris, France (October, 1972).

A similar comprehensive paper on the measurement and analysis of fast neutron spectra in depleted uranium has just appeared⁶ in Nuclear Science and Engineering. This publication gives detailed investigations of several features of the evaluation of the cross-section data for ^{238}U (and also related data such as ^{235}U fission)

and the assessment of alternative data sets. The analysis based on new revised files (such as ENDF/B-III) and higher anisotropic scattering moments is continuing.

The analysis of fast neutron spectra in aluminum and the assessment of aluminum data files is under way and the results are to be published in the coming year.

Following the completion and checkout of a sophisticated sodium facility (and its adjunct facilities), detailed investigations of position-dependent fast neutron angular flux spectra in metallic sodium at room temperature have been initiated. Several modifications and improvements, as required for the sodium system (such as a new target, a new air-cooled titanium electron drift-tube window, etc.) have been completed. The measurements on the sodium assembly have been in progress and are expected to continue into the next year. Paralleling these measurements, analysis of fast neutron spectra in sodium, using ENDF/B files, is also in progress and comparisons of measured and calculated spectra are being initiated for the assessment of data files.

The first preliminary studies of fast neutron transport across a material interface were completed this past year. Fast neutron angular flux spectra were measured at positions in the vicinity of the interface in an aluminum-iron assembly and these were analyzed using one- and two-dimensional transport codes; the effect of several aspects of input data was also investigated. The results of these preliminary studies bring out the importance of such two-region-system measurements in checking aspects of differential data not sensitive to the single-region studies. A paper on this work is being submitted for publication.

The time-of-flight spectrum measurements in the large sodium assembly and the desirability of emphasizing the low energy (few-keV) regions has pointed up the necessity of developing new fast neutron targets with increased neutron yield and a softer source spectrum. To this end, new target designs have been investigated and a target consisting of a spherical steel shell with lead bul-

lets and a tantalum-plate insert cooled by mineral oil, is being brought into operation. It is planned to use this target first in conjunction with the sodium assembly to get a better measurement of the neutron spectra at low energies and at larger distances from the source.

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MEASUREMENT AND ANALYSIS OF FAST NEUTRON SPECTRA IN SODIUM

N. N. Kaushal, A. N. Mallen, B. K. Malaviya and E. R. Gaerttner

During the past year, all the necessary details, both regarding equipment and procedures for making proper fast neutron spectrum measurements on the sodium assembly, were completed.¹ Considerable progress was made in collecting spectrum data at several points in the assembly. We expect that in the next few months we will have a set of spectra covering several angles, each at four different radial positions. These positions are listed in Table 1. The following paragraphs describe various stages of progress made during the past year.

Fabrication and pouring of the "slugs" and "plugs" for filling up the reentrant holes which are not in use, was completed. The "plugs" are 2½-in. O.D. 12-in. long thin-walled cylinders of brass filled with sodium and capped on both ends. The "slugs" are similar except that the ends are open and covered with a thin foil. In the original design this foil was of 5-mil. thick aluminum. However, it was found to be susceptible to pin holes which tended to spread in a humid environment. These foils have been replaced with 5-mil. mylar which is found to be satisfactory. These slugs and plugs are stored in wooden boxes but otherwise in uncontrolled environment without any complications.

An air-cooled welded-construction titanium window for the linac output end was fabricated and installed. This window is several times thinner than the previously used water-cooled aluminum window and thus causes very little scattering of the electron beam. This has resulted in a dramatic improvement in the fraction of the electron beam that can be directed onto the target without "rake-off" in the electron-beam stripper.

Spectrum measurements were carried out using the air-cooled tantalum-lead target. As with measurements made on earlier assemblies, a ¹⁰B-Vaseline detector was used to cover the range up to about 2 MeV and a proton-recoil scintillation detector to cover

the range above 0.5 MeV.² The two spectra are then joined smoothly in the overlap region. Figure 1 shows a typical set of measurements in the zero-degree direction. The spectra are normalized on the basis of total electron beam energy deposited in the neutron source during that run. These spectrum measurements cover an energy range from 10 MeV to well below 1 keV (Fig. 1, however, shows data only down to 10 keV).

The count rates at energies below 5 keV were not very good and a long time was required to collect reasonable statistics. This was particularly true of measurements at points distant from the source and/or at backward angles.

In order to improve this situation, a program was initiated to design and construct a target suitable for use with the sodium assembly and capable of handling higher levels of electron beam power.³ Construction of such a target has been successfully completed. We expect to be able to extend the range of spectrum measurements down to 100 eV using this new target. Some problems have been encountered in obtaining a good overlap in certain cases between the data from the low energy detector and that from the high energy detector. The origin of this difficulty has been traced down to instabilities in the proton-recoil detector. A procedure has been adopted for calibrating the detector prior to every run, using a neutron source in a reproducible geometry and recording the contribution of each phototube to the total signal recorded. Such a test procedure, though admittedly integral in nature, quickly locates faulty or low gain member of the seven phototube set on the detector. Another procedure under consideration is to record the pulse-height spectrum as a function of neutron energy (the neutron energy selection made by time-of-flight) from each phototube. Such a procedure should quickly pinpoint any gain drifts in the detector.

On the analytical side, efforts are being devoted to extending the calculation capability down to energies corresponding to the measurements. This involves extension of the group structure, the available cross-section data, etc. down to 100 eV.

Preliminary transport calculations using ENDF/B-I data have been made using a 49-group cross-section set extending down to 10 keV.⁴ A representative calculation (49-group, ENDF/B-I data, S_{16} , P_8) is shown in Fig. 2, which compares the calculation with the experimental spectrum at 26.5 cm. from the source in the 90° direction ($\mu=0$). The overall agreement is reasonable. However, these results are preliminary and further measurements and analysis are under way to provide more detailed comparisons of measured and calculated spectra at other points for the evaluation of sodium cross-section data.

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3. Linear Accelerator Project Progress Report, January - March 1972, 29, COO-3058-14.
4. This report, p. 106.

FIGURE CAPTIONS

- Fig. 1 Amplitude Normalized Neutron Spectra from 1 keV to 10 MeV, in the Zero Degree Direction ($\mu=1.0$) in the Sodium Assembly; for the Source and $R=10.5''$, $18.5''$ and $26.5''$.
- Fig. 2 Comparison of Calculated and Measured Neutron Spectrum in the Sodium Assembly at $R=10.5''$ and $\mu=0$. The data are preliminary.

Figure 1

Figure 2

Table 1. Radial Distances and Directions of the Points
Selected for Measurements of Neutron Spectra
in the Sodium Assembly

<u>Radial Distance (inches)</u>	<u>Angle (degrees)</u>	<u>Direction Cosine</u>	<u>Hole Number</u>	<u>Hole* Depth (inches)</u>
10.5	0	1.0	1	25.5
	90	0.0	2	36.0
18.5	0	1.0	1	17.5
	33	0.838	2	20.5
	90	0.0	3	36.0
	147	-0.838	2	51.5
26.5	0	1.0	1	9.5
	22.5	6.925	2	11.5
	44	0.717	3	17.0
	90	0.0	4	36.0
	136	-0.717	3	55.0
	157.5	-0.925	2	60.5
34.5	0	1.0	1	1.5
	17	0.957	2	3.0
	31.25	0.855	3	6.75
	50	0.645	4	13.75
	90	0.0	5	36.0
	130	-0.645	4	58.75
	148.75	-0.855	3	65.25
	163	-0.957	2	69.0

*There is provision for five reentrant holes in the assembly. The first one is in a radial direction from the source and the remaining four are parallel to the first at distance of 10.5, 18.5, 26.5 and 34.5 in. respectively. The neutron flux is measured in a direction along these holes.

TARGET DEVELOPMENT PROGRAM FOR FAST AND INTERMEDIATE NEUTRON SPECTRA

A. N. Mallen,^{*} N. N. Kaushal, B. K. Malaviya
and E. R. Gaerttner

Spectrum measurements in the sodium assembly have been restricted to low counting rates and long running times because of the limits of the power handling capabilities of the neutron source. The present source¹ is capable of 600 watts maximum operating power. At power levels above 600 watts, there is a possibility of melting the lead sphere that surrounds the target insert.

A new target has been designed, built and tested for use with the sodium assembly. This target is capable of handling 5000 watts of linac beam power. The target insert, shown in Fig. 1, consists of 5 ea. 1/16-in. thick Ta plates followed by 4 ea. 1/8-in. thick Ta plates enclosed in a double-walled cylindrical aluminum housing. The Ta plates are separated by 1/32-in. gap to provide for coolant flow.

The target insert is embedded in a cylindrical reentrant recess in a 3-5/8-in. diameter hollow stainless steel sphere. The sphere is filled with lead shot and has coolant tubes attached to the surface, as shown in Fig. 2, to provide forced convective cooling. Additionally, a new electron beam stripper was fabricated to guide the electron beam to the center of the target.

The target and stripper are shown in Figs. 3 and 4. This unit is inserted into a 6-in. diameter cylindrical brass housing and will be used for spectrum measurements in the sodium assembly.

The power handling tests of the new target have been performed with both air cooling and oil cooling. With air flow of 6 cfm, the new target was able to handle 1.5 KW of linac power. At this power level the internal temperature of the sphere did not exceed 130°C and the target could probably handle up to 2.5 KW with increased air flow. With light-weight mineral oil as

^{*}Based in part on the Ph.D. Thesis of A. N. Mallen.

the cooling medium, a flow rate of $\frac{1}{2}$ gal./min. and a power level of 3 KW, the maximum temperature of the sphere and coolant remained below 160°F. A discoloration of the oil due to radiation became apparent after 150 KW hours of operation. Modifications are being made to increase the flow rate of the coolant oil to more than one gallon per minute so that the design-objective of 5 KW may be attained.

Measurements have been made of the source spectrum emitted from the oil-cooled target and are presented in Fig. 5. The bare-target spectrum has the same basic shape as the present target, with both old and new targets peaking at ~ 800 keV. When compared with the old target, the new target shows a 20% increase in neutrons with energies below 50 keV. Additionally, though not shown in the figure, there is a relative increase in neutrons of energies greater than 3 MeV, due to direct photoneutron production in the cooling oil.

The relative isotropy of the new target has been measured by means of activation of sulfur and aluminum foils. The principal reactions used for activation were

with threshold energies of 0.921 MeV, 1.8 MeV and 3.1 MeV respectively.² The results are shown in Fig. 6. The angular distribution is seen to peak in the forward direction for the highest energy neutrons. However, for neutron energies below 4.5 MeV, (the effective threshold of the $\text{Al}(\text{n},\text{p})\text{Mg}^{27}$ reaction) the neutron distribution is isotropic within 5 per cent. Since the great majority of source neutrons from the new target have energies below 4.5 MeV, the new target may be considered to be an isotropic source for theoretical calculations.

The higher neutron intensities available from this target will greatly improve signal-to-background ratios for lower energy (≤ 10 keV) neutrons and enable us to extend the range of measurements in sodium down to 500 eV.

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FIGURE CAPTIONS

- Fig. 1 Cross Section of Target Insert with Attached Coolant Tubes.
- Fig. 2 Cross Section of Stainless Steel Sphere (lead shot housing) with Attached Coolant Tubes.
- Fig. 3 Target Insert and Lead Shot Housing.
- Fig. 4 Target and Stripper Assembly.
- Fig. 5 Bare Target Spectrum Measured with Boron Vaseline Detector.
- Fig. 6 Relative Reaction Rates in Aluminum Foils and Sulfur Pellets Placed Around the 3-5/8-in. Diameter Lead Shot Housing with Target Insert.

TARGET INSERT

Figure 1

93

Figure 2

Figure 3

Figure 4

BARE TARGET -- OIL COOLED

Figure 5

Figure 6

FAST NEUTRON SPECTRA IN TWO-REGION SYSTEMS

D. C. Gibbs,* B. K. Malaviya, N. N. Kaushal and E. R. Gaerttner

During the past year, the analysis of preliminary fast neutron spectrum measurements in two-region systems was completed¹; a paper on this work is being submitted for publication.² The motivation for these studies and their significance from the point of view of fast-reactor applications and checks of cross-section data and analytical methods have been discussed in earlier progress reports.^{3,4} Some of the results of the preliminary feasibility studies based on measurements on an aluminum-iron assembly and the approaches to the analysis of these measurements have also been reported earlier.^{4,5} Here we present some additional results and the significant conclusions of these studies.

Both one- and two-dimensional transport codes have been employed in the analysis of several aspects of the two-region data.¹ The two-dimensional transport code DOT⁶ employed a 4-group cross section set, collapsed from a 49-group set which was generated by RPI version of SUPERTOG,⁷ using an MCC⁸-derived weighting spectrum (ENDF/B-I data). An example of the comparison between 4-group DOT calculation and the experimental result is shown in Fig. 1; the amplitude of each group is presented here as a function of position; the geometry of the measurements⁴ and the position being described are indicated in the inset; the experimental result has been collapsed to the same units—flux per group—as the calculation. The disagreement between theory and experiment is greater than the expected experimental error, particularly in group 1 (10 MeV-1.3 MeV). The use of a space-dependent cross-section set improves the agreement in the lower energy groups, but the top-group agreement remains poor.¹

If one considers the top energy group of the 4-group iron set in relation to a one-velocity transport problem, a different analytical approach is possible: the outscattering cross section from the top group can be combined with the absorption cross section to generate a relaxation constant χ , given by⁹

*Based in part on the Ph.D. Thesis of D. C. Gibbs.

$$\chi \approx \sqrt{3\Sigma_t\Sigma_a} \left(1 - \frac{2}{5} \frac{\Sigma_a}{\Sigma_t}\right) \quad (1)$$

The asymptotic ⁰made of the solution of transport equation for a point source may then be expressed by

$$\phi_{as}(r) \sim \frac{e^{-\chi r}}{r} \quad (2)$$

From the measured angular fluxes in the $\mu=0$ direction in the iron region, an experimental value of the relaxation constant χ was derived to be 0.120 ± 0.020 . This compares with a value of 0.1636 computed from Eq. (1) and the input cross sections. The value of Σ_a used in Eq. (1) was 0.05467 cm^{-1} . Of this 0.00017 cm^{-1} is due to actual absorption and 0.00440 cm^{-1} to elastic scattering out of the group. The remainder 0.0501 cm^{-1} is caused by inelastic scattering. If one assumes that the total cross section, being the most easily measured, is the most accurate, a reduction in the inelastic scattering cross section of 30% would bring χ near the experimentally measured value. This assertion is supported in part by a recent measurement of the iron inelastic cross section up to incident neutron energies of 1.8 MeV.¹⁰ This measurement suggests that the ENDF/B-I file data for the 847-keV level in ⁵⁶Fe should be reduced by about 50%. The reduction of the cross section of the 847-keV level alone would not, however, be sufficient to bring about the change in the relaxation constant required by the two-region experiment.

In a separate investigation, foils were loaded into the assembly in a selected hole as a "piggyback" experiment since they would provide a means to obtain some information about the scalar flux in the assembly and would not perturb the angular flux measurements. Of the various materials used, nickel proved to be the most suitable for the purpose. The reaction ⁵⁸Ni(n,p) ⁵⁸Co has a threshold of about 1 MeV with a relatively high peak cross section of 650 mb. at about 8 MeV. To analyze the foil data, the DTF-IV calculated scalar flux spectrum was multiplied by the group averaged ⁵⁸Ni(n,p) ⁵⁸Co cross section to obtain a predicted reaction rate. The predicted reaction rates were then compared with the measured

^{58}Co activity which was corrected for foil weight, time to count and irradiation time. The results are presented using a one-velocity analysis in Fig. 2. The ordinate is plotted in units of $\ln\phi + \ln r$ which by Eq. (2) is equal to a constant plus χr . The slope of the curve is then equal to χ . No attempt was made to obtain a common normalization between the two curves to avoid questions regarding the magnitude of the scalar flux in the assembly. In any case, it is the slope of the two curves which is of principal interest.

The amenability of both the calculated and the experimental data to one velocity analysis is surprisingly accurate and tends to support the use of this approach in the analysis of the angular flux measurements discussed above. The values for χ obtained were 0.174 cm^{-1} from the foils and 0.208 cm^{-1} from the calculation, for an error of about 16%. The magnitudes of the relaxation coefficients are different from those obtained from the angular flux data due to the fact that the scalar fluxes have been multiplied by the $^{58}\text{Ni}(n,p)^{58}\text{Co}$ cross sections which emphasizes higher energy neutrons having greater relaxation constants. However, the error detected is in the same direction and of similar magnitude to that detected in the angular flux measurements. This result lends further support to the assertion that the cross sections used for iron overestimate the degree of spatial relaxation to be expected in iron in the MeV range.

Checks of several different types of cross-section data for iron and aluminum have been possible from this experiment, leading to both confirmation of results from other experiments and, in some cases, to additional exclusive checks of input data. These preliminary studies have served to elucidate and establish several aspects of the usefulness of two-region integral experiments in providing efficient checks of many features of input data and calculational methods pertinent to the core-blanket interface situation.² Based on these studies, it has also been possible to recommend further measurements and analysis of assemblies of iron-uranium or sodium-uranium, for the assessment of data of interest to the LMFBR program.

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FIGURE CAPTIONS

- Fig. 1 Calculated (DOT, 4-Group) and Measured Angular Fluxes of Neutrons Propagating Parallel to the Interface: Spatial Variation.
- Fig. 2 Comparison of Analytical and Experimental (foil-measured) Spatial Relaxation in the Iron Region at High Energies.

Figure 1

Figure 2

ASSESSMENT OF DATA FILES FOR IRON

B. K. Malaviya, N. N. Kaushal, M. Becker, A. Ginsberg
and E. R. Gaerttner

A comprehensive paper¹ on the measurement and analysis of fast neutron transport characteristics in bulk iron from the point of view of checking differential data and calculational methods, was published in Nuclear Science and Engineering during the past year. The measurements provided position-dependent fast neutron angular flux data for a large iron assembly principally in the energy range 10 keV to 10 MeV. The analysis made use of precise transport (S_N) calculations and interpretive approaches based on continuous slowing down theory; transport approximation was employed in the S_N calculations thus emphasizing the analysis of those low and intermediate energy (below 1 MeV) results which were not appreciably affected by anisotropic scattering. The data sets selected for assessment in this study were the files then available: KEDAK, ENDF/B-I and ENDF/B-II.

The analysis of fast neutron spectra in iron is being continually updated so as to include new data files (as they become available) and improved analytical capability. Some further results (not included in Ref. 1), were recently reported² at the Fourth International Conference on Reactor Shielding in Paris, October 9-13, 1972. These results include (a) assessment of the new data set ORNL-1124³ (which, with some modifications, forms the basis of the revised files ENDF/B-III for iron) and (b) the more rigorous interpretation of experiment-theory comparisons at high energies (above 500 keV) by incorporating specific anisotropic scattering (up to P_8 scattering moments) in the analysis. The major updated conclusions² of our data assessment studies are given below. Some figures relating to the effect of anisotropic scattering at high energies, are given elsewhere in this report.⁴

Summary and Conclusions: Assessment of data files for iron:

Best overall agreement is obtained using ENDF/B-I data, a somewhat surprising situation in view of the speed with which that

file originally had to be compiled. Several specific points may be noted:

(1) The 27 keV resonance generally is not represented well, despite its prominence. The KEDAK representation gives best agreement with experiment.

(2) In the 30-300 keV range, the KEDAK, ENDF/B-II and ORNL-1124 files have similar amplitude characteristics, while ENDF/B-I tends to be higher. ENDF/B-I calculations generally give good agreement with experiment, but the spectra with the lower energy data (as from 1124) can be considered acceptable.

(3) At high energies, anisotropic scattering is required for meaningful comparisons with experiment. Of the two files studied with high-order anisotropic scattering, ENDF/B-I appears preferable to 1124.

(4) While ENDF/B-I gives good agreement for this experiment, lack of resolution implies greater errors for very deep penetrations.

(5) Additional direct data measurements would be useful for high energy angular distributions and for total cross sections in the 30-300 keV range.

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CALCULATIONAL METHODS FOR FAST SPECTRUM ANALYSIS

A. N. Mallen,* N. N. Kaushal, B. K. Malaviya and E. R. Gaerttner

The importance of fast spectrum measurements in sodium is to make integral checks of the nuclear data available for sodium and the calculational methods employed. As part of the Spectra Program, calculations have been performed with the one-dimensional transport code DTF-IV¹ using P_0 , P_3 and P_8 scattering.

The model used in these calculations to represent the sodium assembly is shown in Fig. 1. The model consists of four main regions in spherical geometry. The first region contains a "black absorber"² of radius $R=3.81$ cm. The absorption cross sections in this region are sufficiently large so that all neutrons that enter this region are absorbed. The second region contains the neutron source in a small annulus of radius $3.81 \text{ cm} < R < 3.97 \text{ cm}$. The third region is a void region with $3.97 \text{ cm} < R < 8.0 \text{ cm}$. The final region consists of a sodium region with $8.0 < R < 98 \text{ cm}$. In evaluating nuclear data sets, the best cross section information and the best approximations available are to be used. However, many assemblies are simply too complex to use the highest order approximation in theoretical calculations, and lower orders must be used. It is therefore of interest to note how low-order approximations compare with higher-order approximations. In this regard, a number of comparisons were made of flux spectra calculated with P_0 scattering, P_3 scattering and P_8 scattering.

The first item examined was the scalar flux, as predicted by DTF-IV using 49 energy groups, P_{15} quadrature, and 56 radial intervals while varying the order of anisotropic scattering and using ENDF/B-I data. The calculated fluxes were examined at four radii: $R=10.5$, 18.5 , 26.5 and 34.5 inches. A comparison between the P_3 and P_8 calculations show that the P_3 scalar flux is within 1% of the P_8 scalar fluxes for all energies. It can be concluded then that problems involving scalar fluxes in sodium need not be cal-

*Based in part on the Ph.D. Thesis of A. N. Mallen.

culated by any approximation higher than P_3 . An even lower order approximation P_0 may be used if errors as high as 5% in the scalar flux can be tolerated. The calculated errors for radii, $R=10.5, 18.5, 26.5, 34.5$ inches were as high as 3, 2, 4 and 5% respectively with an average error of about 2%.

However, the P_0 approximation, when compared with P_8 does very poorly in determining angular fluxes. In the most forward direction ($\mu=\cos\theta=.9894$), the errors in the flux are very large, in some cases different by a factor of 2 in the high energy (> 500 keV) region. For lower energies (< 500 keV) the P_0 angular fluxes differ from the P_8 fluxes by less than 10%, with the best agreement at the lowest energy. For the same direction, the P_3 approximation does considerably better, differing from the P_8 calculations by as much as 6% at very high energy (> 5 MeV) and less than 1% at low energies.

The same trend was noticed for other angles in addition to the forward angle, though the forward angle emphasized the differences. It can be concluded from these observations that angular flux determinations with a P_0 calculation are adequate only below a few hundred keV, that P_3 calculations are adequate for energies below a few MeV, but that P_8 calculations are necessary for the region above a few MeV.

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FIGURE CAPTION

Fig. 1 Computational Model — One Dimensional Representation of the Sodium Assembly in Spherical Geometry.

ONE DIMENSIONAL MODEL
OF SODIUM ASSEMBLY

NOT DRAWN TO SCALE

Figure 1

NEUTRON EMISSION TIMES IN A PULSED SODIUM ASSEMBLY⁺

A. N. Mallen,* N. N. Kaushal, B. K. Malaviya and E. R. Gaerttner

A knowledge of the emission time effects is important for a correct interpretation of the neutron spectra measured by time-of-flight techniques.¹ The first time moment $\langle t \rangle$, or mean emission time, is included in the measured time-of-flight and must be subtracted to obtain the correct neutron energy. The higher time moments have the effect of "time smearing," resulting in a deterioration of the energy resolution of the system. This effect should be taken into account in the interpretation of structured spectra.

In the course of our experiments on fast neutron transport in a sodium assembly, a simple experiment was performed to obtain information on both counts.² Neutron spectra from a Ta-Pb target was filtered through a 10-in. thick iron stack (placed in the neutron path 10 meters from the source) and the filtered spectrum measured by time-of-flight through a distance of 33 meters. The neutron spectrum from a point in the sodium assembly ($R=16''$, $\theta=141^\circ$) filtered through the same iron filter was then recorded by the same time-of-flight system.

The experimental setup for measuring the two time-of-flight spectra is shown in Fig. 1. The RPI electron linear accelerator, operating with a burst width of 20 nanoseconds was used as the high energy electron source, to provide 70 MeV electrons for the Ta-Pb neutron converter target.

The two time-of-flight spectra are shown in Fig. 2. A comparison of the two spectra shows up some interesting features. The

*Based in part on the Ph.D. Thesis of A. N. Mallen.

⁺A paper based on this material is to be presented at the Winter 1972 meeting of the American Nuclear Society to be held at Washington, D. C. from November 12 to November 17, 1972.

gamma flash, which occurred in channel 165 (not shown in the figure) showed up in essentially one timing channel, thus verifying that the timing and resolution was the same in both cases. Features corresponding to structure in the neutron spectrum, as measured in the sodium assembly, however, are both broadened and shifted to longer times. The shift and broadening get progressively larger with decreasing neutron energies.

Converting the two time-of-flight spectra to energy spectra, we obtain the spectra shown in Fig. 3. The resonance structure shown corresponds to minima in the iron filter total cross section between 10 keV and 1 MeV. It is immediately apparent from the figure that there is an energy shift to lower energies in the spectra measured in the sodium assembly (top curve in the figure). Additionally, there is a considerable amount of resolution broadening of the iron resonance minima caused by the uncertainty in the emission time. The uncertainty in the emission times is represented by the quantity

$$\sigma = (\langle t^2 \rangle - \langle t \rangle^2)^{\frac{1}{2}}$$

This is the standard deviation about $\langle t \rangle$ of the time distribution of the neutron population, and represents the time "smear" of the neutron distribution about $\langle t \rangle$.

For an impulse source $S^{(0)} \delta t$ as used in these measurements, the time moments may be found by successive solution of the steady-state transport equation and are given by⁵

$$\langle t^n \rangle = \frac{\int_0^\infty t^n \varphi(\vec{r}, E, \vec{n}, t) dt}{\int_0^\infty \varphi(\vec{r}, E, \vec{n}, t) dt} = \frac{\varphi^{(n)}}{\varphi^{(0)}}$$

where $\varphi^{(0)}$ is the solution to the transport equation with a steady-state source $S^{(0)}$ and $\varphi^{(n)}$ is the solution to the steady-state transport equation using a source defined by

$$S^{(n)} = \frac{n}{v} \varphi^{(n-1)}$$

Successive solutions of $(n+1)$ transport equations thus provide the n^{th} time moments.

First and second time moments, $\langle t \rangle$ and $\langle t^2 \rangle$, calculated using the one-dimensional transport theory code DTF IV³ in 49-group, spherical geometry, P_{15} quadrature, and employing both the isotropic (P_0) scattering model and the P_3 scattering model. The group constants were obtained from the SUPERTOG code⁴ using ENDF/B-I sodium cross sections. The geometry consisted of a black absorber source region, a small vacuum annulus, and a 6-ft. diameter sodium region.

The scalar first moment (P_3 scattering) is shown in Fig. 4 for the sodium assembly for the source, and for radii of 10.5, 18.5, 26.5 and 34.5 inches respectively. It is seen that at lower energies, the radial dependence of the emission times decreases, but nonetheless remains significant. Of special interest is the source, which when embedded in the assembly, shows emission times in excess of 50 nanoseconds for energies below 100 keV. However, the angular distribution of emission times falls rapidly to less than a few nanoseconds for angles in the forward direction, and source emission times in sodium thus do not constitute a problem. A comparison of the P_3 and P_0 calculations for the mean emission times shows that both calculations are essentially the same in predicting scalar time moments in sodium. The calculated P_0 emission times exceed the calculated P_3 emission times by less than 2% for all points in the assembly. This indicates that the scalar moments are not very sensitive to anisotropic scattering. The sensitivity of the time moments to the source spectrum was also investigated by calculating the emission time in sodium with a source spectrum that peaked 500 keV lower than the actual spectrum, which peaked at ~800 keV. The results of this comparison indicate that at 10 inches from the source, an error as large as 14% may occur in the emission time. This error is further reduced with distance from the source. Considering that this 14% error in emission time was caused by a 62% error in energy of the source spectrum, it is obvious that the calculation of emission times is not very sensitive to the source spectrum representation.

The angular dependence of the mean emission time has also been

calculated and is shown in Figs. 5, 6 and 7 for neutron energies of 340 keV, 172 keV, and 26.5 keV respectively. At high energies (340 keV) the mean emission time is seen to be extremely angular dependent for all radii in the sodium, with the most extreme differences in the most forward angles and at points near the source. At intermediate energies (172 keV) the angular variations are smaller but still very significant. Only at much lower energies (26.5 keV) and at points not too near the source, does the angular dependence of the emission times become small. It is thus clear that the emission time corrections that have to be applied to the sodium data must be angular mean emission times.

Listed in Table 1 are the calculated scalar time moments, angular time moments, and the experimentally observed emission times. It can be noted from the table that the angular moments (for an angle of 139°) are in general larger than the scalar moments. Since the flux in the sodium assembly is forward-peaked, and the scalar moment is just the flux weighted angular time moment; i.e.,

$$\langle t(r, E) \rangle = \frac{\int_{\Omega} \langle t(r, E, \vec{n}) \rangle \varphi(r, E, \vec{n}) d\vec{n}}{\int_{\Omega} \varphi(r, E, \vec{n}) d\vec{n}}$$

it is expected that for back angles the angular time moment will be greater than the scalar time moment. The experimental results are generally in agreement with the calculation except at energies below 130 keV, where the calculated emission times fall outside the experimental error and there are discrepancies of about 20%. However even at these energies, the relative error in the measured time-of-flight is less than 1%. Considering the resolution broadening at lower energies and the subjective nature of choosing the center of the broadened peaks, the agreement between theory and experiment is quite good.

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FIGURE CAPTIONS

- Fig. 1 Experimental Arrangement for
(a) Filtered beam measurement of bare target spectrum.
(b) Filtered beam measurement of the Sodium Assembly from
 $R = 16$ inches, $\theta = 141^\circ$.
- Fig. 2 Comparison of Neutron Time-of-Flight Spectra Filtered Through 10 inches of Iron from
(a) Bare Neutron Target
(b) with Target Embedded in the Sodium Assembly and the Neutron Spectrum from $R = 16''$ and $\theta = 141^\circ$.
- Fig. 3 Comparison of Neutron Energy Spectra Filtered Through 10 inches of Iron for
(a) the Sodium Assembly from $R = 16''$ and $\theta = 141^\circ$
(b) Bare Neutron Target.
- Fig. 4 The Scalar First Time Moment (Mean Emission Time) for the Sodium Assembly for the Source and Radii $R = 10.5, 18.5, 26.5$ and 34.5 inches (P_3 Anisotropic Scattering).
- Fig. 5 Angular Dependence of Mean Emission Times for Energy Group 24 ($387 \text{ keV} > E > 302 \text{ keV}$) for the Source, and Radii $10.5, 18.5, 26.5, 34.5$ inches.
- Fig. 6 Angular Dependence of Mean Emission Times for Energy Group 29 ($183 \text{ keV} > E > 161 \text{ keV}$) for the Source, and Radii $10.5, 18.5, 26.5, 34.5$ inches.
- Fig. 7 Angular Dependence of Mean Emission Times for Energy Group 42 ($28.2 \text{ keV} > E > 24.9 \text{ keV}$) for the Source, and Radii $10.5, 18.5, 26.5, 34.5$ inches.

Figure 1

TIME-OF-FLIGHT NEUTRON SPECTRUM
THRU 10 INCH IRON FILTER

Figure 2

Figure 3

MEAN EMISSION TIMES IN SODIUM

Figure 4

ANGULAR MEAN EMISSION TIME ($E=340$ KEV)

Figure 5

ANGULAR EMISSION TIME ($E=172$ KEV)

Figure 6

ANGULAR EMISSION TIME (E=26.5 KEV)

Figure 7

Table 1. Neutron Emission Times in a Sodium Assembly

Energy keV	Energy Shift keV	Time-of- Flight (nsec)	<u>Calculated Time Moment</u> *		<u>Experimental** Mean Emission Time (nsec)</u>	<u>Error*** (nsec)</u>
			<u>Scalar (nsec)</u>	<u>Angular (nsec)</u>		
656	25	2844	64	73	94 $\pm$ 31	+21
344	13	2969	127	141	98 $\pm$ 31	-43
305	18	4219	127	141	142 $\pm$ 31	+ 1
271	16	4500	147	162	139 $\pm$ 31	-23
217	13	5031	172	184	164 $\pm$ 31	-20
183	13	5500	213	229	190 $\pm$ 31	-39
165	11	5781	213	229	187 $\pm$ 31	-42
130	10	6500	257	273	211 $\pm$ 31	-62
81.1	5.5	8281	373	389	316 $\pm$ 31	-73
24.5	2.6	15187	790	804	862 $\pm$ 31	+58

*DTF IV Code, 49 Group, P15 Quadrature, P3 Scattering, ENDF/B-1 data.

**Data corrected for increased flight path length.

***Experimental minus calculated emission times.

LEAD SLOWING-DOWN SPECTROMETER

D. S. Cramer,* R. E. Slovacek* and E. Bean*

A 75 ton (6' x 6' x 6') lead slowing-down spectrometer has been assembled and experimental studies of its characteristics are underway. The impetus for this work follows from the need to assay fissile material in irradiated fuel rods with a non-destructive technique.

The assay technique involves the detection of fast (high energy) fission neutrons from fissile material. The fission is produced by an initial burst of neutrons which diffuse outward from the target and slow down in a large volume of lead. Lead is essentially an elastic scatterer below 0.5 Mev and the neutron burst slows down uniformly with a time focusing. The result is a relationship between the time after the burst in μs and the average interrogating neutrons energy in keV given by¹:

$$\langle E \rangle = \frac{183}{(t + 0.3)^2} \quad (1)$$

and a varying resolution² of about $\frac{\Delta E}{E} \approx 20\%$. The expression (1) is the equivalent of a TOF system with a 5.917-meter flight path.

By selecting the proper time interval (2 μs to 25 μs), an optimum can be achieved for sensitivity to small amounts of fissile material in the presence of large amounts of non-fissile host material; that is, after 2 μs the average energy of the interrogating flux is below the fission threshold for the non-fissile material. From 2 μs out to 25 μs the average energy decreases from 25 keV down to 250 eV which is above the resolved resonance and self-shielding energy region. Below 250 eV, in the resolved resonance region, counting data indicates characteristic resonance structure and can be used to estimate self-shielding effects of the non-fissile material and/or trace quantities of fissile material.

The spectrometer consists of 5770 lead bricks of 99.99% purity. The brick surfaces were carefully cleaned to eliminate any impuri-

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ties, especially hydrogenous compounds such as cutting oil and lead carbonate. The cube was stacked on a 2-ft. high platform of I-beams which spreads the weight to 100 sq. ft. of floor space and allows space for external shielding consisting of previously available boron oxide "logs." In addition, the cube is covered with 0.030 in. cadmium sheet. The RPI LINAC delivers an electron beam (about 60 meV) to the center of the cube placed at the far end of the target room. The beam passes through a stripper-collimator before going through a 0.001 in. titanium window into a helium drift section extending from the cube surface to the tantalum target of the cube center. The target and titanium window are cooled by a helium circulating system. The target is typically run at 10 to 500 watts, providing an average neutron production of $\sim 1 \times 10^{12}$ neutrons/second at 500 watts. The target and lead temperatures are monitored. Additional (γ, n) production is gained from the lead which necessarily surrounds the tantalum target.

The bricks are stacked such that a maximum experimental flexibility is provided by four detector channels, eight interrogation channels, one beam channel, and one reentrant channel. These channels are filled with brick when not in use. A typical flux in the center of an interrogation channel is $\sim 1 \times 10^8$ neutrons/cm²-sec at 500 watts target power.

An on-line acquisition system employing a Hewlett-Packard 2116B computer is used to take time-of-flight (TOF) data. The software and hardware combination allows up to six detector channels to be recorded simultaneously from zero time out to several hundred microseconds in 1024 channels/detector where the channel widths are adjustable upward from 0.03 μ s.

Many detector systems are under consideration. Boron-10 detectors have been used as flux monitors to plot the decay of the interrogating neutron flux. Using the relationship (1) and dividing out the B-10 cross section from the monitor response, the flux as a function of energy can be fit by:

$$\phi(E) = \frac{C}{E^\alpha} \quad (2)$$

The constant α from the data is 0.77; calculated from Fermi-age theory, it is 0.78, and from Monte Carlo time-independent calculations, it equals 0.80. By calculation, it is shown that α varies from 0.63 to 0.80 to 0.83 by going from 50 to 75 to 100 tons of lead (which increases the cube edge from 1.3 to 1.8 to 2.0 meters).

Helium-4 recoil, NE213 pulse shape discrimination detectors, NE451 (proton-recoil Hornyak buttons) pulse-height discrimination detectors, stilbene pulse shape discrimination detectors, and fission threshold detectors are under consideration. The helium-4, NE213, NE451 and stilbene detectors all indicate a large response to the interrogating flux. This problem is still being studied. The Th232 and U238 detectors are used to follow the rapid decay of the high energy component of the interrogating flux above their thresholds. Their response dies away by 10^{-3} in less than 2 μ s. Three U-238 detectors containing 3 milligrams (total) of U-238 placed against 25 grams U-235 can provide 0.3% counting statistics in 30 minutes in the energy region above the self-shielding region, at a target power level of 500 watts, and with the background 6% of the foreground. Turning this around, a 1-gram U-238 detector can easily detect hundredths of a gram of fissile material. The U-238 fission detector data clearly show the structure in the resonance region for U-235 although partially flattened by self-shielding. For trace amounts of U-235, one can use the resonance region. When embedded in the lead the fission detectors are essentially insensitive to the gamma burst from the LINAC. A large amount of effort has gone into minimizing the sensitivity to r.f. pickup and gamma flash by carefully shielding the detectors, electronics and cables.

To study the characteristic signatures of U-233, U-235, Pu-239 in the resonance region, fission detectors made of these isotopes separately were placed in the spectrometer. The cross-section structure characteristic in the resolved resonance region of each isotope is seen and labelled the "signature" for that iso-

tope. By using detailed cross-section values and folding them together with a 45% broad square-wave energy resolution function, comparisons are made to the signatures corrected for the flux decay. Using this technique, good visual agreement is achieved for Pu-239. The signatures for U-233, U-235 and Pu-239 are distinctly different in the resolved region.

Using dilute samples, one can obtain usable group average cross sections for (n,γ) and (n,f) since the resolution of the spectrometer is comparable to the MUFT energy widths of equal lethargy.

Monte Carlo calculations are continuing to study many basic characteristics of the lead cube as a slowing down spectrometer and as an assay tool. Some effects that are considered are lead purity, optimum lead geometry, optimum detector positions, sample composition, sample geometry, linac target perturbations, detector cross talk, room return background, etc. These effects are in the range of several per cent or less and can be corrected to better than 0.1%.

The comparisons of the data to the calculations for the Fermi-age (α of Eq. (2)) can be used to place an upper limit on the integral effect of any absorption in the lead and to obtain some indication as to the adequacy of the inelastic (down-) scattering matrix.

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MEASUREMENT OF TIME-DEPENDENT SLOWING-DOWN SPECTRA IN LEAD

N. N. Kaushal

During the past year, construction of a 6-ft. cube assembly of lead (total weight 75 tons) was completed by KAPL (Knolls Atomic Power Laboratory) group studying the use of a lead slowing-down spectrometer for thermal breeder fuel assay.¹ However, in addition to its use as a lead slowing-down spectrometer, the assembly is ideally suited for studying the neutron slowing-down processes both elastic and inelastic, without side effects from neutron fission reactions as was the case with a depleted uranium assembly.

With that basic purpose in mind, a few measurements of time-dependent neutron spectra were carried out as 'piggy back' experiments using the ³He solid-state neutron spectrometer described earlier in these reports.² The measurements were carried out at approximately 20 watts of electron beam power. The γ -flash was essentially absent and the neutron flux was adequate to provide meaningful data in a few hours. A few problems were encountered due to RF noise pickup. These were reduced to tolerable levels by use of double shielded cables and isolating the ground-loop currents.

Some representative data are shown in Fig. 1. The figure shows the time-decay of neutron flux in the lead assembly at $R \approx 50$ cm, for several energy groups in the range 230 to 680 keV. The total time range extending up to 500 μ sec is broken into two parts. The first two microseconds are covered with a channel width of 62.5 nsec to study the short-term slowing down and the remainder of the range is covered in 16 μ sec steps to investigate long-term behavior. No background has been subtracted from the data as shown. However, this correction is less than ten per cent of the signal.

The data show in detail the neutron slowing-down process in the keV region. In the short term process, the high energy flux peaks faster and decays faster compared to the lower energy flux. At the end of the two microsecond period, the flux is down by two

orders of magnitude. This short-term behavior is essentially similar for all energy groups shown and is mostly responsible for the velocity focusing characteristics of a lead slowing-down spectrometer.

In the intermediate term between 2 μ sec and 70 μ sec, the flux decreases by another order of magnitude. This intermediate term behavior is also quite similar in various energy groups except for small increases in decay rate with increasing neutron energies. However, after this period the data show a sharp difference in the rate of decay between neutron energies above and below 500 keV. For energies above 500 keV this long-term decay rate is essentially similar to that in the intermediate term but drastically slower for energies below 500 keV.

Although the lack of energy resolution in the spectrometer does not permit a detailed observation below 100 keV, the trends seem to indicate that at much lower energies the short and intermediate term effects tend to merge as one. The first peak which essentially represents a direct wave propagation is weakened in amplitude and secondary wave of slowed down neutrons picks up in amplitude and peaks later. At low energies, the flux is dominated by the secondary wave.

The marked difference in the long-term behavior can be explained in terms of the onset of inelastic slowing down. Because of the increased slowing down effectiveness, the neutron flux at these energies continues to decrease very rapidly. Whereas, at energies below the first inelastic threshold, the only mechanism for flux decay is due to elastic slowing down, the capture and leakage being small in a large lead assembly. The decay constant therefore is quite small in comparison.

It thus appears that the time-dependent slowing-down is quite sensitive to the details of the inelastic scattering cross sections, particularly near the threshold for this reaction. The differential measurements in this region are quite uncertain and the time-dependent slowing-down can provide a valuable integral check on these data.

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FIGURE CAPTION

Fig. 1 Time-dependent Behavior of Scalar Neutron Flux at Several Selected Energies, in a Pulsed Lead Assembly at Approximately 50 cm Radial Distance from the Source.

Figure 1

REACTOR PHYSICS AND ENGINEERING - THEORETICAL

REACTOR PHYSICS AND ENGINEERING - THEORETICAL

The theoretical effort is concerned with problems of theory and analysis important in our experimental program in particular, and in fast reactor development in general.

We have capitalized on our anisotropic capability to calculate spectra based on high-order anisotropic scattering. The results, to be discussed in more detail within individual sections, both provide new information based on comparison with experiment and confirm earlier conclusions reached on the basis of low energy comparisons alone.

Because of the long running time associated with processing ENDF/B data and generating group constants, we have investigated the possibility of using approximate methods to improve efficiency. We have developed and tested a method based on continuous slowing down theory for generating full elastic transfer matrices. The method appears to provide acceptable accuracy with substantially reduced running time. The method has potential for use in "Bondarenko-type" codes.

Our approach to time-dependent spectra seems to be working out successfully. The strengths and limitations of the procedure seem to have been determined, and we now are in the process of applying it to materials of interest in the fast neutron spectrum program.

Our treatment of spectra at interfaces has evolved to a matrix extension of our earlier infinite medium approach. Integral transport theory (escape probabilities) is used to represent leakage between zones. Separable kernels obtained in our infinite medium work are used for the slowing down process. Relations between slowing down density and collision density analogous to those familiar from infinite medium theory are obtained except that they are vector relations and the slowing down parameters are matrices. The model has been programmed and is being tested.

We have, in the past, been successful in utilizing results of continuous slowing down theory (generalized for inelastic scattering) to understand the relationships between measured spectra and precise calculations. To enhance our ability to make such sensitivity studies, we have initiated activity to make use of interactive graphics and time-sharing with the CDC-6600 in this process. It is hoped that this initial investigation will pave the way for much broader usage of the interactive concept, so programming is being oriented toward general usage.

RAPID CALCULATIONAL METHODS FOR ELASTIC TRANSFER MATRICES

M. Becker

Because of the long running times associated with generating multigroup sets from ENDF/B, we undertake to determine whether approximate rapid techniques of adequate accuracy could be developed. We have developed such methods on the basis of continuous slowing down (CSD) theory.

Our first concern was with calculating total removal (i.e., transfer to just one group) with high order anisotropy. In effect, this objective can be considered to be a generalization to anisotropic matrices of the approach used in standard LMFBR "production" codes (ETOX, ENDRUN) for isotropic (with the transport approximation) problems. Equations and results were given in a previous progress report.¹ A paper describing the method and results has been accepted for presentation at the Winter 1972 Meeting of the American Nuclear Society.

The approach has been extended and tested for cases in which elastic transfer to more than one group is possible. We shall describe briefly the procedure for slowing down two groups with a uniform group structure.

The elastic transfer cross section for the k th Legendre moment to the second group (when only two groups are possible) is given by

$$\sigma_k^{g \rightarrow g+2} = \frac{1}{\phi_k^g} \int_{u_{g+1}-\epsilon}^{u_g} du' \int_{u_{g+1}}^{u'+\epsilon} du'' \phi_k(u') P_k[\mu_0(U)] \sum_{k'=0}^K \frac{2k'+1}{2} \sigma_{sk'}^c(u') P_{k'}[\mu_c(U)] \left[-\frac{d\mu_c}{dU} \right] \quad (1)$$

$$U = u'' - u' \quad (2)$$

$$\epsilon = \ln \frac{1}{\alpha} \quad (3)$$

Notation is standard. In CSD, we generally take Taylor expansions of collision densities. In this case, we expand

$$\sigma_{Sk'}^c(u') \phi_k(u') = \sigma_{Sk'}^c(u_g) \phi_k(u_g) + \dots \quad (4)$$

To date, we have considered only the first term in the expansion, as in Eq. (4), which is typical of Fermi age models. Equation (4) leads to

$$\sigma_k^{g \rightarrow g+2} = \frac{\phi_k(u_g)}{\phi_k^g} \sum_{k'=0}^K \frac{2k'+1}{2} \sigma_{Sk'}^c(u_g) \int_{u_{g+1}-\epsilon}^{u_g} du' \int_{u_{g+1}}^{u'+\epsilon} du'' \quad (5)$$

$$P_k[\mu_o(U)] P_{k'}[\mu_c(U)] \left(- \frac{d\mu_c}{dU} \right)$$

The double integral in Eq. (5) can be converted to single integrals in a manner suggested by Henryson.² Consider an integral of the form

$$I = \int_{u_{g+1}-\epsilon}^{u_g} du' \int_{u_{g+1}}^{u'+\epsilon} du'' f(U) = \int_{u_{g+1}-\epsilon}^{u_g} du' \int_{u_{g+1}-u'}^{\epsilon} dU f(U) \quad (6)$$

Reversing the order of integration leads to

$$I = \int_{\Delta}^{\epsilon} dU f(U) \int_{u_{g+1}-U}^{u_g} du' = \int_{\Delta}^{\epsilon} dU (U-\Delta) f(U) \quad (7)$$

where Δ is the group width.

With the conversion to a single integral, we have

$$\sigma_k^{g \rightarrow g+2} = \frac{\phi_k(u_g)}{\phi_k^g} \sum_{k'=0}^K \xi_{kk'}^{g \rightarrow g+2} \sigma_{Sk'}^c(u_g) \quad (8)$$

$$\xi_{kk'}^{g \rightarrow g+2} = \frac{2k'+1}{2} \int_{\Delta}^{\epsilon} dU P_k[\mu_o(U)] P_{k'}[\mu_c(U)] \left[- \frac{d\mu_c}{dU} \right] (U-\Delta) \quad (9)$$

In practice, we prefer to integrate over center of mass angle, so we evaluate Eq. (9) by

$$\sigma_{k'k}^{g \rightarrow g+2} = \frac{2k'+1}{2} \int_{-1}^{\mu_c(\Delta)} d\mu_c [U(\mu_c) - \Delta] P_k(\mu_c) P_{k'}(\mu_c) \quad (10)$$

$$\mu_c(\Delta) = 1 - \frac{(A+1)^2}{2A} (1 - e^{-\Delta}) \quad (11)$$

Analogous developments can be used to generate expressions for $\sigma_k^{g \rightarrow g+1}$ and $\sigma_k^{g \rightarrow g}$. Numerical results have been found to be acceptable and the running times attractive. With this method used in SUPERTO, roughly a factor of eight in overall running time is achieved.*

The procedure outlined here has implications for the shielding factor method used in ETOX and ENDRUN. In that approach one computes group constants for several values of background cross sections to set up a self-shielding factor table. With this approach, very little additional work is required to consider various background cross sections σ_0 . With the scalar flux, for example, the σ_0 enters in the weighting flux

$$\phi_0(u) = \frac{1}{\sigma_t(u) + \sigma_0} \quad (12)$$

$$\phi_0^g = \int_{u_{g-1}}^{u_g} du \frac{1}{\sigma_t(u) + \sigma_0} \quad (13)$$

The major additional work is the simple integration of Eq. (13).

We recommend consideration of this approach for "production" codes where either multiple group transfer or anisotropic scattering or both are of interest.

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1. Linear Accelerator Project Progress Report, April - June 1972, 61, COO-3058-21.
2. H. Henryson, II, Nucl. Sci. Eng., 43, 235 (1971).

*See Table 1

Table 1

Selected Isotropic Elastic Group Constants for Sodium ($\Delta u = .125$)

	<u>Fast CSD Method</u>	<u>Standard SUPERTO</u>
$\sigma_{47 \rightarrow 47}$	1.89	1.88
$\sigma_{47 \rightarrow 48}$	2.89	2.90
$\sigma_{47 \rightarrow 49}$	.28	.28
$\sigma_{46 \rightarrow 46}$	1.82	1.81
$\sigma_{46 \rightarrow 47}$	2.78	2.80
$\sigma_{46 \rightarrow 48}$	.27	.26
$\sigma_{45 \rightarrow 45}$	1.75	1.75
$\sigma_{45 \rightarrow 46}$	2.71	2.72
$\sigma_{45 \rightarrow 47}$	.26	.26
$\sigma_{44 \rightarrow 44}$	1.71	1.70
$\sigma_{44 \rightarrow 45}$	2.64	2.65
$\sigma_{44 \rightarrow 46}$	.26	.25

ANISOTROPIC ANALYSIS OF FAST NEUTRON SPECTRA
IN URANIUM, IRON AND ALUMINUM

A. Ginsberg* and M. Becker

We have applied our ability to generate suitably weighted anisotropic group constants to provide sets for iron (ENDF/B-I ORNL-1124), uranium (ENDF/B-I, II) and aluminum (ENDF/B-I) and have utilized these sets in transport calculations for comparison with spectrum experiments. (We also have processed data for sodium.)

Comparison with experiment for uranium leads to good agreement at high energies except that calculations dip below the experiment in the low MeV range. The location of this dip corresponds to the peak in inelastic effectiveness. (At higher energies, other processes start to compete with inelastic scattering.) This result indicates that inelastic effectiveness at the peak should be lower. ENDF/B-II is better than ENDF/B-I. (The inelastic cross section is similar, but the secondary distribution is harder, though not sufficiently so to yield good agreement with experiment.) ENDF/B-III has a still harder secondary distribution — a change in the right direction. The magnitude will be assessed in the coming fiscal year.

Our conclusions regarding low energy inelastic scattering¹ have been confirmed by our high energy results. If the small ^{235}U impurity is included in the calculation, far too many high-energy neutrons are calculated to be present. This is because the over-predicted low-energy flux leads to far too many ^{235}U fissions. Best agreement with experiment is obtained when ^{235}U is not included in the calculations.

High energy agreement between theory and experiment is good in all directions with the exception of the common problem of the dip corresponding to inelastic peaks. This observation indicates that the angular distributions are satisfactory for transport calculations.

*Based in part on the Ph.D. Thesis of A. Ginsberg.

A paper on the iron results has been accepted for presentation at the Fourth International Conference on Reactor Shielding (Paris, October 1972). Figures 1-5 show selected spectra for ENDF/B-I and ORNL-1124. The influence of anisotropic scattering is evident from the forward direction spectra. (Recall that low energy disagreement in the forward direction in iron is due to a boundary effect.) While both ENDF/B-I and ORNL-1124 give good high-energy agreement in the forward direction, the high-energy ENDF/B-I results give better high-energy agreement in the 90° direction. Both files underpredict the spectrum at very high-energy.

Best overall agreement still is given with the ENDF/B-I data file. From the differences between data files and the comparisons between theory and experiment, current areas of uncertainty appear to be in high-energy angular distributions, total cross sections in the 30-300 keV range, and the parameters of the 27 keV resonance.

Comparison between theory and experiment also has been made for aluminum. Transport calculations were not repeated for ENDF/B-II data because of the great similarity between the group constants from the two files. Interpretation of this comparison is complicated by the greater influence of leakage on the measured results in aluminum relative to other assemblies. Interpretation of the results and formulation of final conclusions are still a matter of internal discussion which we hope to resolve shortly.

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1. N. N. Kaushal, B. K. Malaviya, M. Becker, E. T. Burns and E. R. Gaerttner, "Measurement and Analysis of Fast Neutron Spectra in Uranium Depleted in the Uranium-235 Isotope," Nucl. Sci. Eng., 47, 330 (1972).

FIGURE CAPTIONS

- Fig. 1 Comparison of Experimental and Theoretical (ENDF/B-I data) Flux in Iron Using Transport Approximation at $r=6''$, $\mu=1.0$.
- Fig. 2 Comparison of Experimental and Theoretical (ENDF/B-I data) Flux in Iron Using P_8 -Scattering at $r=6''$, $\mu=1.0$.
- Fig. 3 Comparison of Experimental and Theoretical (ORNL-1124 data) Flux in Iron Using P_8 -Scattering at $r=6''$, $\mu=1.0$.
- Fig. 4 Comparison of Experimental and Theoretical (ENDF/B-I data) Flux in Iron Using P_8 -Scattering at $r=10''$, $\mu=0$.
- Fig. 5 Comparison of Experimental and Theoretical (ORNL-1124 data) Flux in Iron Using P_8 -Scattering at $r=10''$, $\mu=0$.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

INITIAL CALCULATIONS WITH HANFORD DATA LIBRARIES FOR ^{238}U

M. Becker

Hanford Engineering Development Laboratory (HEDL) has produced fast neutron group constant sets. These sets are of particular interest because of the HEDL role in the design of the Fast Test Reactor (FTR, formerly FFTF). We considered two sets; one (ENDF-143) based on ENDF/B-II¹, and the other (FTR-300) based on modifications to ENDF/B-II to improve agreement with critical assemblies.² Computer programs have been written to read HEDL data, generate infinite medium flux spectra and prepare results for plotting.

The first question we addressed was the sensitivity of spectra to scattering self-shielding in the unresolved resonance region. Indeed, the desire to study this sensitivity was an important part of our desire to utilize the HEDL data. Our previous studies³ with uranium were based on group constants generated with MC². The MC² code applies self-shielding corrections to unresolved capture but not to unresolved scattering. The HEDL group sets contain self-shielding corrections for both scattering and capture. Thus, we are interested not only in evaluation of the HEDL sets as an end in itself, but also in testing the validity of an assumption involved in our ENDF/B assessments.

Figure 1 shows a comparison of spectra with and without scattering self-shielding for the FTR-300 set. The differences are noticeable, but fairly small. The magnitudes of the differences observed are not sufficient to change any of the conclusions we have previously published. Similar results were obtained with the ENDF-143 data.

The second question considered was a comparison of FTR-300 and ENDF-143 spectra. These are plotted together in Fig. 2. The spectra are fairly similar. Thus, the serious inadequacies found in ENDF/B data³ have not been eliminated in FTR-300. Two differences are observed which we shall discuss separately.

At energies above the spectrum peak (and particularly Group 11), the FTR-300 flux is higher than the ENDF-143 flux. Based on comparisons with experiment, this change is in the direction to increase discrepancies. We studied the group constants to determine the source of the difference. Consider, in particular, the situation for Group 11, where the difference is greatest (1.47×10^{-5} vs. 1.27×10^{-5}). Inspection of the in-scattering cross sections from other groups indicated very similar values. The sources to the group thus seemed similar, so we considered the removal cross section

$$\sigma_r = \sigma_c + \sigma_d + \sigma_i - \sigma_i^{g \rightarrow g} \quad (1)$$

where c, d, i denote capture, elastic downscatter, and inelastic. Table 1 provides the data. We thus see a substantial reduction in the inelastic cross section leading to a reduction in the removal cross section on the order of eleven per cent. This accounts for most of the thirteen per cent difference.

In our previous study³ of ^{238}U , we concluded that inelastic effectiveness at low energies should be reduced. However, the change called for there was of a broader and smoother nature than the highly concentrated effect associated with FTR-300.

A second area of difference is below the peak where the FTR-300 flux is lower than the ENDF-143 flux. This also would be in the direction of poorer agreement with experiment. Inspection of the data sets indicates that the capture and elastic removal

TABLE 1

Comparative Data for Group 11 (Barns)

	<u>FTR-300</u>	<u>ENDF-143</u>
σ_c	.2157	.2153
σ_d	.1829	.1829
σ_i	.3327	.4202
$\sigma_i^{g \rightarrow g}$	.0	.0
σ_r	.7313	.8184

cross sections are similar, but that the inscattering inelastic cross sections differ significantly, as shown in Table 2.

The two effects observed obviously are related in that the low inelastic cross section which led to the high FTR-300 flux above the flux peak leads to the low inscattering source and low flux below the flux peak.

Table 2 and Fig. 2 also provide a general indication of sensitivity of low energy flux to inscattering sources, and, therefore, of the indirect dependence of our judgments about capture on inscattering sources. From a mathematical point of view, the inscattering could correspond to inelastic scattering or to the recently postulated $(n;n',\gamma)$ reaction. From the simple neutron balance viewpoint, the $(n;n',\gamma)$ reaction implies replacing neutron capture with large-energy-change inelastic scattering. (This would not be appropriate for the fuel manager who looks to conversion ratio or to the shielder who looks for the gamma ray.) We shall look further into this general question in the future.

It is conceivable that the principal desirable change regarding inelastic scattering should be reduction, as indicated in Ref. 3, but that there might be desirability of an effective simultaneous increase of inelastic influence at very low energies. This type of change would affect our conclusion that absorption is too strong and might predict increased low energy fluxes in critical assemblies. We shall withhold judgment on this possibility until it can be checked further.

TABLE 2

Inelastic Transfer at Low Energies

	<u>FTR-300</u>	<u>ENDF-143</u>
$\sigma_{i,11 \rightarrow 12}$	.2172	.2637
$\sigma_{i,11 \rightarrow 13}$	.0991	.1329
$\sigma_{i,11 \rightarrow 14}$	.0164	.0239
$\sigma_{i,12 \rightarrow 14}$	.0112	.0162
$\sigma_{i,12 \rightarrow 15}$	.0198	.0285
$\sigma_{i,12 \rightarrow 16}$	.0182	.0263

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FIGURE CAPTIONS

Fig. 1 Sensitivity to Scatter Self-Shielding - FTR-300.

Fig. 2 Comparison of FTR-300 and ENDF-143 U-238 Fluxes.

Figure 1

Figure 2

CONTINUOUS SLOWING DOWN THEORY AND INTERFACES

G. Epstein* and M. Becker

Our approach to interface problems has evolved to an extension of our space-independent continuous slowing down model¹ to an integral transport form. We previously have considered extensions to space-dependence through age theory and through multigroup discrete ordinate calculations using the separable kernel analogy to generate group constants. The integral transport approach has the advantage, as will be shown below, that equations can be solved in a simple manner. In addition, in plane-geometry, collision probabilities can be evaluated easily permitting analysis with a refined energy structure. In this manner, the transition in spectral line structure can be represented.

The collision density in zone m is given by

$$F_m(u) = [1 - P_m(u)] \int_0^u du' F_{Sm}(u') f_m(u' \rightarrow u) + \sum_{n \neq m} P_{nm}(u) \int_0^u du' F_{Sn}(u') f_n(u' \rightarrow u) \quad (1)$$

If we define

$$I_n = \int_0^u du' F_{Sn}(u') f_n(u' \rightarrow u) \quad (2)$$

and if we consider F_m and I_m to be components of vectors F and I , then we can express Eq. (1) as

$$F = P I \quad (3)$$

$$P = \begin{pmatrix} 1 - P_1 & P_{21} & \dots & \dots \\ P_{12} & 1 - P_2 & & \\ P_{13} & & & \\ \vdots & & & \\ \vdots & & & \end{pmatrix} \quad (4)$$

We also can define a slowing down density quantity as

$$q_m(u) = \int_u^\infty du'' [1 - P_m(u'')] \int_0^u du' F_{Sm}(u') f_m(u' \rightarrow u'') \\ + \sum_{n \neq m} \int_u^\infty du'' P_{nm}(u'') \int_0^u du' F_{Sn}(u' \rightarrow u'') \quad (5)$$

which can be integrated over the u'' variable to yield

$$q_m(u) = \sum_n \int_0^u du' F_{Sn}(u') K_{nm}(u', u) \quad (6)$$

$$K_{nm} = \left. \begin{aligned} & \int_u^\infty du'' [1 - P_m(u'')] f_m(u' \rightarrow u'') \\ & \int_u^\infty du'' P_{nm}(u'') f_m(u' \rightarrow u'') \end{aligned} \right\} \begin{aligned} & n = m \\ & n \neq m \end{aligned} \quad (7)$$

Conservation of neutrons requires that

$$\frac{dq_m}{du} = - \frac{\Sigma_{am}}{\Sigma_{tm}} F_m - P_m I_m + \sum_{n \neq m} P_{nm} I_n \quad (8)$$

or, in matrix form, using Eq. (3)

$$\frac{dq}{du} = -AF \quad (9)$$

$$A = \frac{\Sigma_a}{\Sigma_t} + (I - P)P^{-1} \quad (10)$$

where Σ_a/Σ_t is a diagonal matrix.

So far, what has been done is general. Stacey² has used essentially the same formalism for pure elastic moderation. At this point, we introduce the separable kernel

$$F_m(u' \rightarrow u) = h_m(u') g_m(u'') \quad (11)$$

Equation (6) becomes

$$q_m = \sum_n g_{nm} J_n \quad (12)$$

$$J_n = \int_0^u du' F_{Sn}(u') h_n(u') \quad (13)$$

$$g_{nm} = \begin{cases} \int_u^\infty du'' [1 - P_m(u'')] g_m(u'') & n = m \\ \int_u^\infty du'' P_{nm}(u'') g_m(u'') & n \neq m \end{cases} \quad (14)$$

In matrix form

$$q = G J \quad (15)$$

A little algebra leads to

$$\left(\frac{dG}{du} \right)^{-1} G^{-1} \frac{dq}{du} + q = \left(\frac{dG}{du} \right)^{-1} hF_S \quad (16)$$

which is of the form

$$\gamma \frac{dq}{du} + q = \xi F_S \quad (17)$$

where the slowing down quantities γ and ξ are matrices rather than scalars. Evaluation of the matrices in Eq. (16) is simpler than may appear at first glance, if one applies matrix identities for inverses and derivatives.

Equations (9) and (16) demonstrate that in an integral transport formulation, the application of separable kernels leads to continuous slowing down theory and resulting procedural advantages directly analogous to those observed in infinite medium theory. Computer codes have been developed to apply this approach to interfaces. The separable kernels used are those obtained for individual materials in our infinite medium work. Several transport and numerical problems were encountered, but the principal difficulties appear to have been resolved just recently. Preliminary calculations indicate that the procedure is operational. Testing and evaluation are in progress.

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REENTRANT HOLE PERTURBATION IN CURVED GEOMETRY

M. Danchak* and M. Becker

The reentrant hole model has been made operational, and the principal programming and data handling problems appear to have been resolved. The program now is being checked out and applied to experimental configurations. There are some preliminary indications that some of the high-energy discrepancies between theory and experiment (particularly above five MeV) may be due at least in part to reentrant hole effects. During the early part of the coming fiscal year, we should firm up our conclusions as to the utility of the code and the influence of the reentrant hole effects.

The approach used is an extension of the plane-geometry model developed at RPI.¹ Basically, a curvilinear geometry problem is used to generate a wall-streaming source for use in a plane-geometry perturbation calculation. The model accounts for angular distribution effects and the lack of azimuthal symmetry around the hole.

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*Based in part on the Master's Engineering Project of M. Danchak.

TIME-DEPENDENT SPECTRA

S. Kang* and M. Becker

Our simple time-analytic approach has been demonstrated to be successful in multigroup application to intermediate mass non-multiplying media encountered in our spectrum program (e.g., iron, sodium). A paper on the approach was presented at the June 1972 American Nuclear Society Meeting.¹ The technique has yielded good results in situations (the vicinity of strong resonances) where we have had difficulty getting good results with a finite-difference transport code.

We have attempted to apply the technique to a very heavy material, lead, since there was a possibility of utilizing a lead slowing down spectrometer. Because of the elastic focusing effect (i.e., in a slowing down process due to elastic scattering alone, the spectral shape at low energies and long times becomes very narrow and sharply peaked) and because of the energy range of interest (in a spectrometer, one is interested in energies down to epithermal; i.e., order of eV, whereas in our fast spectrum work, the lower limit has been on the order of 1 keV), numerical problems arise in dealing with the lead spectrometer. Some of these have been resolved, but considerably more effort would be required to handle the full energy range. In view of the secondary priority of lead as a material of interest, we have postponed further development of the technique along this line.

Our current area of emphasis is application of the technique as it has been developed to fast reactor materials to determine whether greater sensitivity to some types of data (e.g., inelastic levels) can be inferred from time-dependent measurements than from static measurements.

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*Based in part on the Ph.D. Thesis of S. Kang.

SUBCRITICAL REACTOR KINETICS

M. Becker

A recently initiated activity has been an investigation of the theoretical foundation behind the use of the tangent- θ method¹ of reactor noise analysis to measure "lifetimes," and to infer generation times.² This approach has been somewhat controversial because generation time is not a physical observable. Our goal has been to determine explicit relationships between the time constant measured and the generation time and to determine potential limitations on utilizing the relationships in both fast and thermal reactors. We have separated the formulation into that of a transfer function approach utilizing noise analysis as the mechanism for measuring the transfer function. This simplifies matters considerably, since it is much easier to derive expressions for the transfer function directly than for the cross-spectral-density. An initial assessment should be completed in time for the first quarterly report of the coming fiscal year.

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INSTRUMENTATION DEVELOPMENT

RENSSELAER INTERACTIVE GRAPHICS ANALYSIS SYSTEM

M. Danchak,* M. Becker and W. R. Moyer

In the last quarterly report¹ broad objectives were outlined for an interactive graphics system utilizing the PDP-15 and CDC-6600 computers. Since that report, more concrete plans have emerged and work has been initiated on RIGAS (the Rensselaer Interactive Graphics Analysis System.) Based on the common usage of iterative techniques throughout the nuclear field, this system will be designed to accept varied inputs and serve as a monitor to guide the analyzer through his comparison of theoretical and experimental results and the theoretical predictions that follow. As shown in Fig. 1, three major tasks are involved: preparation of a test problem, design of the controlling software, and construction of the necessary interface equipment. These will be done concurrently and merged in the final stages.

Slowing down theory was chosen as the test problem not only for its suitability, but also because the sensitivity of neutron spectra to nuclear data is of great interest in the Fast Reactor program, thus providing an immediate and important application of this analysis system. The programs FLUFB, RAGE, ZINN1 and ZINN2 must be modified to run under the Courant Institute's time-sharing (INTERCOM) rules. Once each has been successfully executed, they will be coupled so as to perform interactively under teletypewriter control. The main problem envisioned in this area is adherence to the current limitation of 60K of core at N.Y.U.

Programming of the PDP-15 appears to require the major effort in this system. This machine must function as an intelligent, extremely fast teletypewriter. Human engineering factors are on par in importance with data handling, since the conceptual design entails natural language. The analyzer is just that — no prior experience with the system or programming knowledge will be required. Instructions to the machine will

*Based in part on the Ph.D. Thesis of M. Danchak.

be via obvious interactions with graphical presentations and conversation through a keyboard. One therefore requires a library of words and word phrases from which the PDP-15 can assemble the appropriate instructions to either modify the display or transmit to the CDC-6600 for further computation. A number of these programs, such as record retrieval and data selection, must be written to run on either machine, dependent on the input data source.

The design of the interface is predicated on the capabilities of the Courant Institute. Initially a 300 baud data link is planned, with hopes for a 2000 baud link in the near future. This area will remain the least detailed for the present, pending implementation of Courant's new time-sharing/batch system.

Performance to Date

Thus far, the program FLUFB has been run satisfactorily in batch mode. RAGE and ZINN1 are in the checking-out process and reworking for time-sharing should commence soon. The CSISRS format was adopted as the standard for input, regardless if it is point-wise cross sections or neutron flux. This allows easy conversion of previous tabulated data by mere inclusion of a bibliography and certain key words. The PDP-15 display package has progressed to the point where the machine can read a variable number of entries, strip off the bibliographies and store separately, and allow selection of energy to be displayed from within the limits of the entire energy range. Work is currently being done on the optimum display of this data.

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FIGURE CAPTION

Fig. 1 Rensselaer Interactive Graphics Analysis System Work Flowsheet.

WORK FLOW SHEET

Figure 1

*PH.D. DEGREES IN NUCLEAR ENGINEERING GRANTED BY
DIVISION OF NUCLEAR ENGINEERING

<u>NAME</u>	<u>TITLE OF THESIS</u>
Gibbs, D. Clark	"Studies of Fast Neutron Spectra Across a Material Interface"
Golovchenko, Jene A.	"On the Deduction of Continuum Potentials from Planar Channeling"
Merrill, Guy L. Jr.	"A 'Static' Mass Spectrometric Assay of Xenon and Krypton Arising from Low Level Burnup of ^{235}U "

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