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LINEAR ACCELERATOR PROJECT

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Rensselaer Polytechnic Institute
Troy, New York 12181

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MASTER

TABLE OF CONTENTS

NEUTRON CROSS SECTIONS

NEUTRON CROSS-SECTION PROGRAM

The neutron cross-section program included investigations into fission, capture, capture gamma spectra, scattering and total cross sections. Measurements were made on approximately fifteen isotopes.

By combining a relatively old technique, the lead slowing down spectrometer, with the Linear Accelerator, we have an extremely powerful means for detecting fission in mass regions and energy regions where it was formerly impossible to observe experimentally. The results of this for ^{238}U have been published in <u>Physical Review Letters</u>, <u>31</u>, No. 4, 247 (1973).

Prompt neutron multiplicity measurements were finished for ^{233}U, ^{235}U and ^{239}Pu. Analysis of the U results is complete and a paper is in preparation.

Capture and total cross-section measurements were made on Rh, ^{151,153}Eu and ^{105}Pd. High resolution capture measurements to about 200 keV were made on ^{61}Ni and ^{54}Fe. Data on ^{58}Fe and ^{64}Ni are being analyzed.

All the measurements mentioned thus far used refinements of techniques pioneered at Rensselaer, namely:

(1) Measurement of neutron multiplicity as a function of neutron energy in the thermal and eV range using a linear accelerator.

(2) High energy, high resolution neutron capture measurements in the keV to hundreds of keV range on low capture structural materials using a linac.

(3) High neutron intensity measurement of micro-barn fission cross sections using a linear accelerator and lead slowing down spectrometer.

The neutron capture gamma spectra facility became fully operational this year as is shown by the results on natural Fe, Ni, ^{54}Fe and ^{60}Ni. This development comes at a time of increased interest in gamma heating effects. One paper is in preparation on ^{60}Ni and Fe.

Precision total cross-section measurements on ^{235}U and ^{239}Pu were made from 0.5 to 30 MeV. Typical accuracies are ±1% and good agreement is obtained in energy regions where older data exist.

Differential elastic scattering measurements were performed on Fe and Ni.

The experimentally observed correlation between total radiative widths and reduced neutron widths in Cr and Ni isotopes was followed up by a theoretical analysis. The results of this show that non-statistical effects are important in the capture process of these nuclei. The practical meaning of this is that it is not possible to predict average capture cross sections of structural materials on the basis of a few measurements in restricted energy regions.

SUBTHRESHOLD FISSION INDUCED BY NEUTRONS ON ^{238}U

R. C. Block, R. W. Hockenbury,
R. E. Slovacek,* E. B. Bean* and D. S. Cramer*

A recent lead slowing-down spectrometer measurement of neutron-induced fission in a ^{238}U fission chamber indicated a large fission component near 800 eV, whereas no effect was observed in a blank chamber of identical construction. One plausible interpretation of this measurement was subthreshold fission in ^{238}U, although measurements by Silbert and Bergen[1] seemed to indicate that ^{238}U would have too small a fission cross section in this energy region to account for the large fission counting rate. In order to test for subthreshold fission in ^{238}U, it was decided to carry out a high-resolution time-of-flight beam experiment and see if the large fission component near 800 eV could be resolved into the fine structure characteristic of ^{238}U resonances in the first potential well.

The experiment was conducted at the Rensselaer LINAC laboratory at a 10.1-m flight path. Five fission ionization chambers, each 2.54 cm diam. by 12.5 cm long, were coated with a total of 0.66 g of ^{238}U. The only significant impurity in the ^{238}U was 27 ± 6 ppm of ^{235}U, with less than 0.3 ppm of ^{233}U, ^{234}U and ^{236}U. The data were collected over the energy range from 0.2 eV to over 100 keV.

An auxiliary measurement was also carried out with a ^{235}U (93% enriched) fission chamber in the same geometry to normalize the ^{238}U subthreshold fission cross section to the known ^{235}U fission cross section.

In this measurement the following were observed: (1) distinct fission resonances below ~60 eV which correspond to ^{235}U resonances, (2) a smoothly varying fission rate above ~100 eV attributed to ^{235}U fission, and (3) several prominent clusters of fission resonances attributed to subthreshold fission in ^{238}U. Two strong clusters were observed near 720 and 1210 eV and weaker groups were observed near 2.5, 7.5, 11, 15, 27 and 35 keV.

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The results show two characteristic groups of fission resonances, with the fine structure occurring at the same position as the ^{238}U resonances. This is interpreted via the Strutinsky model[2] as subthreshold fission with the fine structure corresponding to levels in the first well and the gross structure to levels in the second well. The average spacing of the groups in the second well, based on the observation of three fission clusters in the first ≈3000 eV, is $D_{II}=1000\pm400$ eV, compared to a spacing of D_I of about 14 eV in the first well. The level spacing D_{II} corresponds to an excitation energy of about 2.6 MeV, implying that the second minimum discussed by Strutinsky[2] and Lynn[3] lies about 2.2 MeV above the first minimum in the double-humped potential barrier. It is interesting to note that the fission strengths appear anticorrelated to the neutron strengths; i.e., when Γ_n^o is small, the fission peak is large. This anticorrelation behavior has been observed in subthreshold fission in other nuclei,[4,5] and is predicted by Lynn.[3,7]

The ^{238}U fission cross section is deduced from this experiment by normalizing to the fission occurring in the 27 ± 6 ppm of ^{235}U in the fission chamber.

The data have been analyzed for fission parameters, and the results are listed in Table 1. In Column 1 is listed the energy of the most prominent resonance in each subthreshold fission group. In Column 2 are listed the group fission areas A_f^G obtained by integrating the fission cross section over all the resonances comprising the subthreshold group. Column 3 lists the fission area A_f for the prominent resonance in each fission group. Columns 4 and 5 list the neutron and radiative widths taken from Ref. 6. The fission widths of the 720- and 1210-eV resonances can be obtained from the data listed in Table 1 from the following expression for the fission area:

$$\begin{aligned} A_f &= \int \sigma_f \, dE = \tfrac{1}{2} \pi \sigma_o \Gamma_f \\ &= 2\pi^2 \lambda\!\!\!^{-}{}_o^2 g \Gamma_n \Gamma_f / (\Gamma_n + \Gamma_f + \Gamma_\gamma) \quad , \end{aligned} \tag{1}$$

where the thin-sample approximation is used for the integration of a Breit-Wigner single-level resonance, σ_0 is the peak total cross section at resonance, $\lambda\!\!\!^-_0$ is the reduced neutron wavelength at the resonance energy E_0, and Γ_n, Γ_f and Γ_γ are the neutron, fission, and radiation widths, respectively.

There exists some confusion about what value of Γ_γ should be used in Eq. (1). The average Γ_γ for the low-energy s-wave resonances in ^{238}U is 23 meV,[6] and if this value is used in Eq. (1), we obtain the fission widths listed in Column 5 of Table 1. This 23 meV represents the radiation width in well I of the double-humped fission barrier. On the other hand, it may be argued that the strong fission resonances at 720 and 1210 eV are almost pure class II levels[3,7] and that the radiation width for a level in well II should be used in Eq. (1).

The relationship between the radiation widths in wells I and II is given by Eq. (15) of Ref. 7 as

$$\frac{\Gamma_\gamma^{\ I}}{\Gamma_\gamma^{\ II}} \approx \frac{E - \delta^{I}}{E - \epsilon_0 - \delta^{II}} \, \frac{\alpha_{II}^{\frac{1}{2}}}{\alpha_{I}^{\frac{1}{2}}} , \qquad (2)$$

where E is the excitation energy above the bottom of the first well, α refers to the coefficient in the exponential level density formula, δ is the pairing energy gap, and ϵ_0 is the energy difference between wells I and II. Assuming $\alpha_I \approx \alpha_{II}$ and $\delta^I \approx \delta^{II} \approx 0.7$ MeV, and taking the value of $\epsilon_0 \approx 2.2$ MeV deduced from this experiment, and setting E equal to the binding energy of 4.78 MeV, the radiation width in well II is 4.9 meV. The fission widths based on this lower radiation width are listed in Column 6 of Table 1. Thus the fission widths range from a maximum value in Column 5 assuming the class I radiation width to the minimum value in Column 6 assuming the class II radiation width. The quoted error of about 25% in Columns 5 and 6 results primarily from the uncertainty in the ^{235}U content of the ^{238}U fission chambers.

These results can be compared to the keV energy measurements of Silbert and Bergen[1] by summing the ^{238}U fission counts over the two neutron energy intervals $10 \le E_n \le 30$ keV and $30 \le E_n \le 100$ keV and are shown in Table 2.

Within the experimental errors both measurements are in good agreement in this energy range. It is thus interesting that we agree with Silbert and Bergen in the average ^{238}U fission cross section, but that they did not report the observation of these fission clusters near 720 and 1210 eV.

Table 1. ^{238}U Fission Parameters

E_o (eV)	A_f^G (b eV)	A_f (b eV)	Γ_n (meV)	Γ_f (meV) [Γ_γ=23 meV]	Γ_f (meV) [Γ_γ=4.9 meV]
720	0.45 ± 0.12	0.31 ± 0.08	1.2[a]	1.2 ± 0.3	0.29 ± 0.07
1210	0.19 ± 0.05	0.11 ± 0.03	9.0[a]	0.12 ± 0.03	0.051 ± 0.013

[a] Ref. 3

Table 2. ^{238}U Average Fission Cross Section

Energy Range (keV)	Average fission cross section: This experiment (μb)	Average fission cross section: Ref. 1 (μb)
10-30	87 ± 26	61 ± 24
30-100	40 ± 12	36 ± 14

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390f

PROMPT NEUTRON MULTIPLICITY MEASUREMENTS FOR NEUTRON-INDUCED FISSION OF ^{233}U AND ^{235}U

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

After an extensive rebuilding of the nubar detector electronics and logic system as reported previously,[1] the measurements on ^{233}U and ^{235}U have been completed and a paper for publication is in preparation.

The results of the experiment are presented in Figs. 1 to 4 for four of the five sets of data. Nubar in the thermal region of both ^{233}U and ^{235}U (Figs. 1 and 2) is seen to be relatively constant, to within 0.1%.

The ^{235}U resonance nubar values show a separation into two groups, separated by about 0.5%. The two resonances with the smallest errors, 8.79 eV and 19.3 eV, are observed to be in different groups and are also noted to have different spin assignments (the 8.79 eV resonance has J=3 and the 19.3 eV resonance has J=4) from scattering measurements[2,3]. With that observation, we have made tentative spin assignments based on nubar groupings as shown in Table 1. Included in Table 1 are spin assignments from several authors. The agreement of this set of spin assignments and others is good. Best agreement is with the scattering measurements.

The ^{233}U resonance nubar results also show a resonance-to-resonance variation of the same magnitude as for ^{235}U. However, there is no obvious separation into groups as found for ^{235}U.

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*Based in part on the Ph.D. thesis of R. L. Reed, now at Savannah River.

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1. Linear Accelerator Project Progress Report, October - December 1972, COO-3058-29.
2. F. B. Simpson et al., Nucl. Phys. A164, 34-48 (1971).
3. F. Poortmans et al., in Proceedings of the Second International Conference on Nuclear Data for Reactors, (Helsinki, 1970), 449.
4. S. Weinstein, R. L. Reed and R. C. Block, in "Physics and Chemistry of Fission," IAEA, Vienna (1969) paper #IAEA-Sm-122/113.
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7. R. B. Graves et al., BNL-17604.
8. W. R. Kane, Phys. Rev. Letters 25, #14, 953 (1970).
9. M. Asghar et al., Phys. Rev. Letters 26B, #11, 664 (1968).

FIGURE CAPTIONS

Fig. 1 Region-Averaged Nubar Values for ^{235}U Thermal Fission (0 to 10 eV).

Fig. 2 Region-Averaged Nubar Values for ^{233}U Thermal Fission (0 to 10 eV).

Fig. 3 Nubar Values for ^{235}U Resonances (5 to 30 eV).

Fig. 4 Nubar Values for ^{233}U Resonances (5 to 40 eV).

Table 1. Resonance Spin Assignments for ^{235}U

	Nubar			Scattering		γ-Ray, Multiplicity			
E_o	This Work	(4)	(5)	(2)	(3)	(6)	(7)	(8)	(9)
	3								
26.40	3								
25.55	3								
24.32	3								
23.65	3				(4)	4			
22.95	3	3	3			3			3
21.10	3	3				3			
19.3	4	4	3	4	4	4			4
18.05	4	4	4						3
16.67	(3)	4	4			3			3
16.10	4	4	3			3	4		(4)
15.45	4		3			3			3
12.39	4	4	4	(4)	3	4	3		4
11.67	4	4	4	4	4		4		4
10.16	4		3						3
9.13	(4)		4			3			3
8.79	3	3	3	3	3				3
7.08	3	3	3			3			3
6.39	3	4	4			4		3	4
4.85	4		4					4	(4)
1.145	3		3					4	3
0.290	3							3	

( ) indicate uncertain assignments

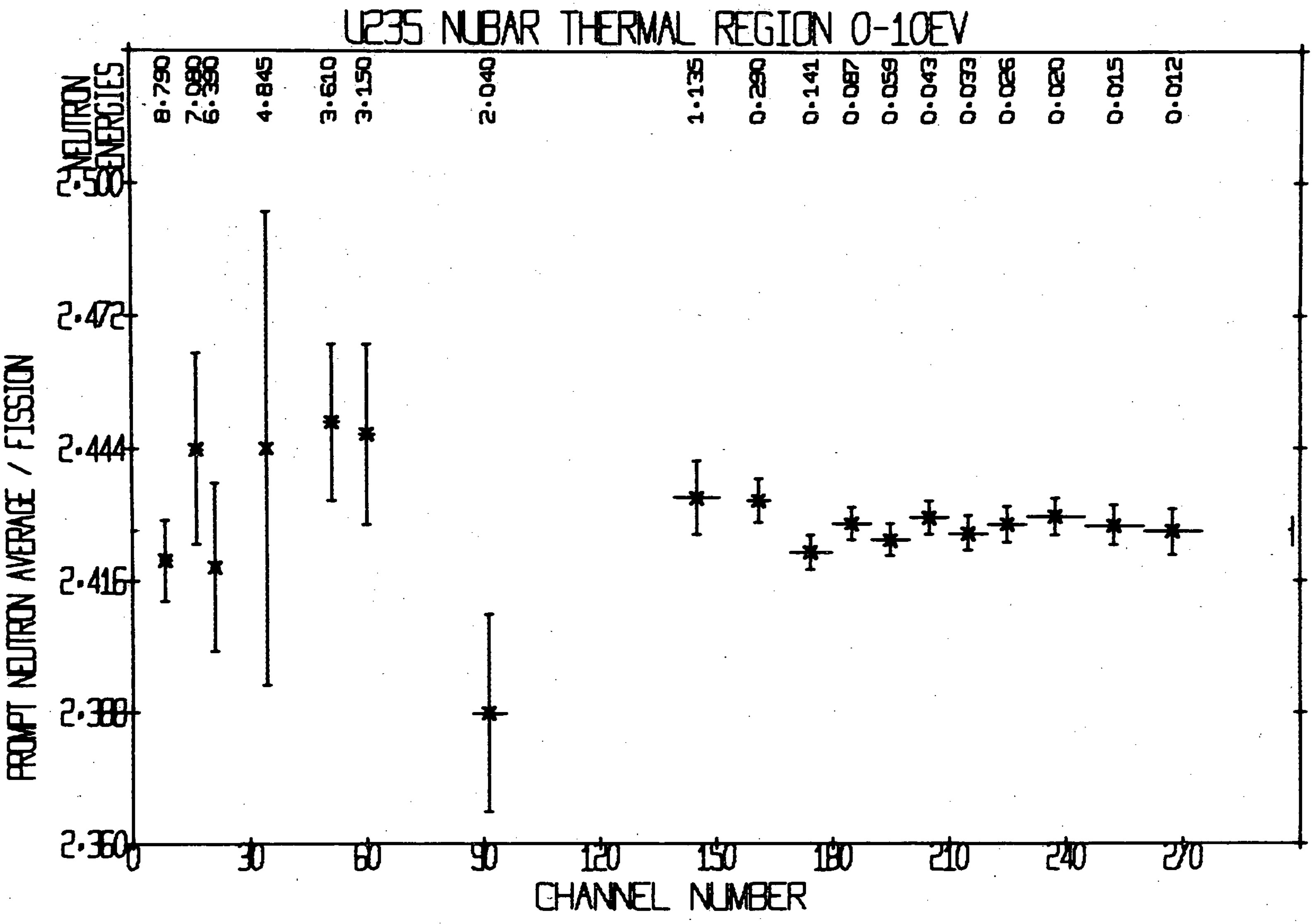
U235 NUBAR THERMAL REGION 0-10EV
NEUTRON ENERGIES
8.790
7.080
6.390
4.845
3.610
3.150
2.040
1.135
0.290
0.141
0.087
0.059
0.043
0.033
0.026
0.020
0.015
0.012
PROMPT NEUTRON AVERAGE / FISSION
2.500
2.472
2.444
2.416
2.388
2.360
0
30
60
90
120
150
180
210
240
270
CHANNEL NUMBER

Figure 1

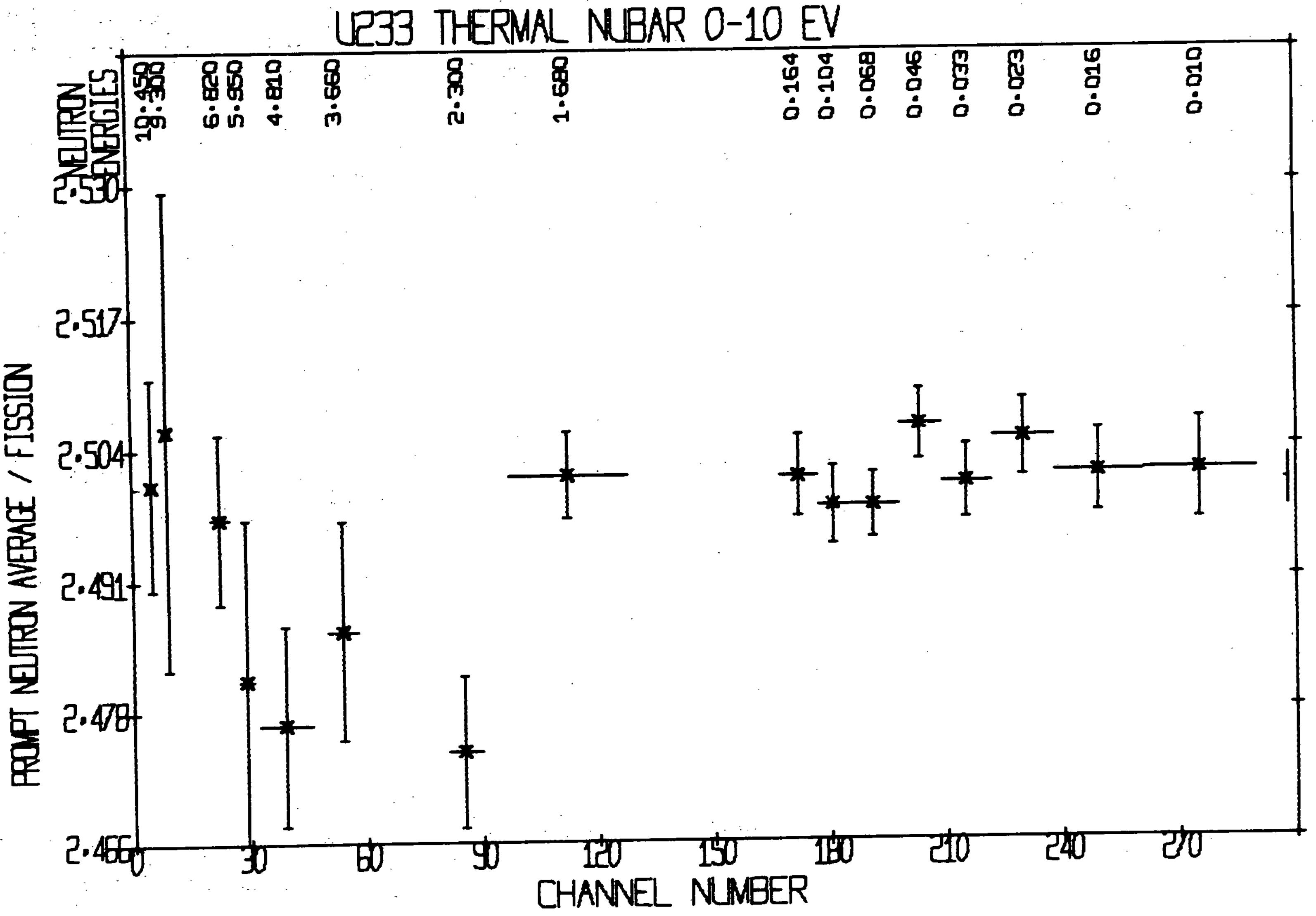
U233 THERMAL NUBAR 0-10 EV
NEUTRON ENERGIES
10.450
9.300
6.820
5.950
4.810
3.660
2.300
1.680
0.164
0.104
0.068
0.046
0.033
0.023
0.016
0.010
PROMPT NEUTRON AVERAGE / FISSION
2.530
2.517
2.504
2.491
2.478
2.466
0
30
60
90
120
150
180
210
240
270
CHANNEL NUMBER

Figure 2

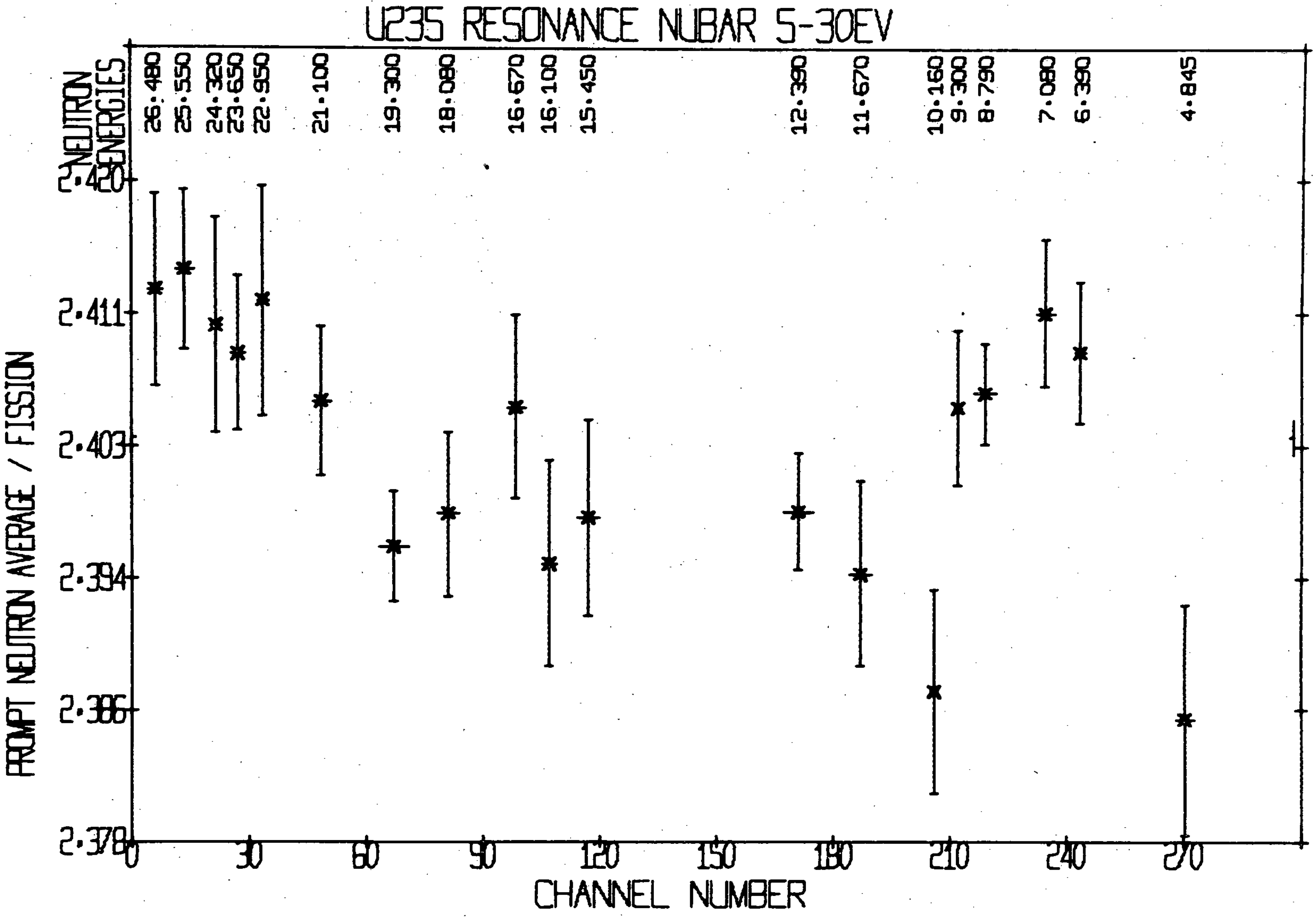
U235 RESONANCE NUBAR 5-30EV
NEUTRON ENERGIES
26.480
25.550
24.320
23.650
22.950
21.100
19.300
18.080
16.670
16.100
15.450
12.390
11.670
10.160
9.300
8.790
7.080
6.390
4.845
PROMPT NEUTRON AVERAGE / FISSION
2.420
2.411
2.403
2.394
2.386
2.378
0
30
60
90
120
150
180
210
240
270
CHANNEL NUMBER

Figure 3

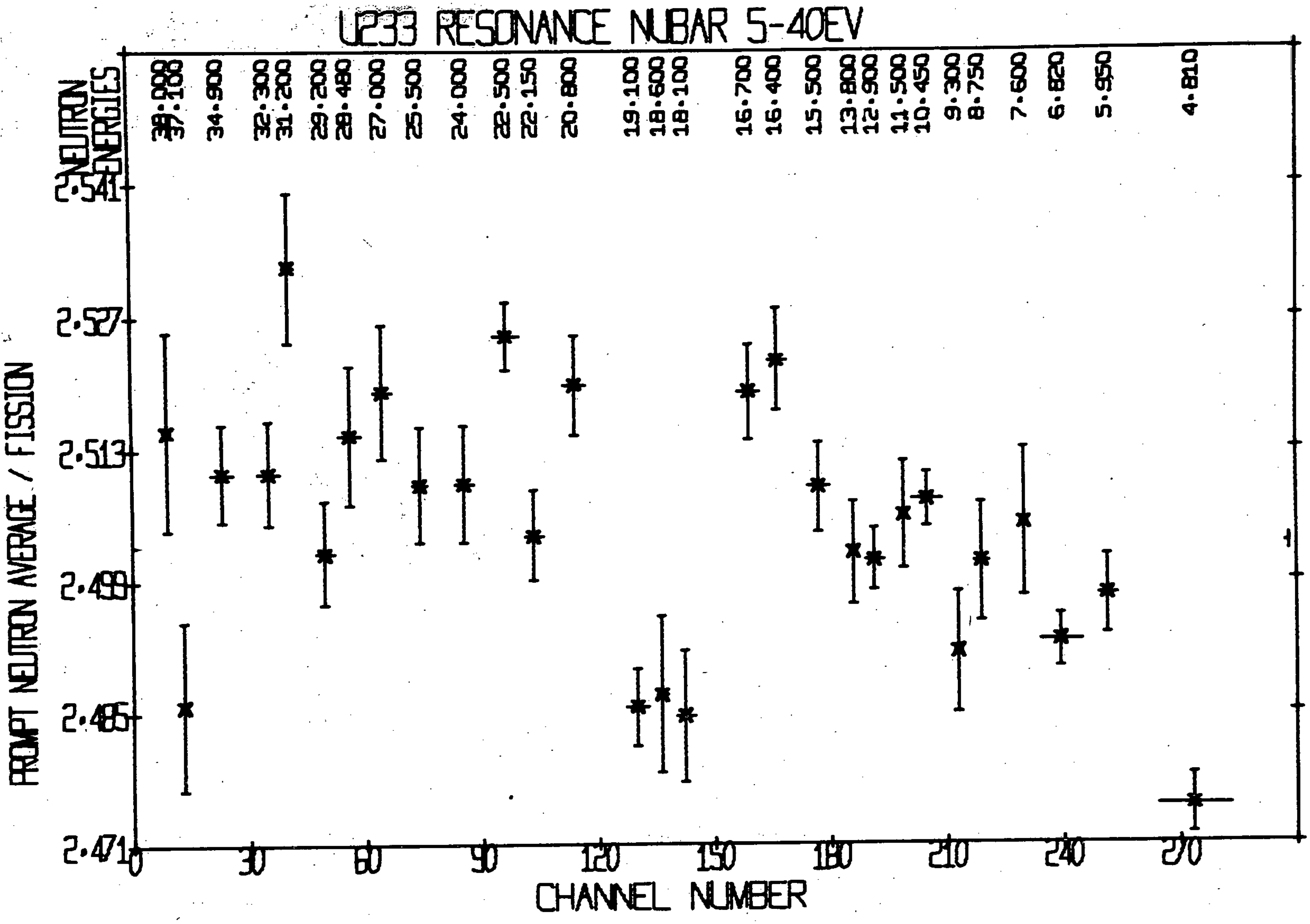
U233 RESONANCE NUBAR 5-40EV
NEUTRON ENERGIES
38.000
37.100
34.900
32.300
31.200
29.200
28.480
27.000
25.500
24.000
22.500
22.150
20.800
19.100
18.600
18.100
16.700
16.400
15.500
13.800
12.900
11.500
10.450
9.300
8.750
7.600
6.820
5.950
4.810
PROMPT NEUTRON AVERAGE / FISSION
2.541
2.527
2.513
2.499
2.485
2.471
0
30
60
90
120
150
180
210
240
270
CHANNEL NUMBER

Figure 4

RESONANCE AND THERMAL $\overline{\nu}$ MEASUREMENTS ON ^{239}Pu

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

Nubar measurements were made on ^{239}Pu essentially from thermal energies to 100 eV. A 1.4 gm ^{239}Pu fission chamber[1] was used together with a 0.75-meter diameter liquid scintillator at a flight path of about 25 meters. A description of the data acquisition system has been given previously.[2] The data were taken in two sets of runs, the first set covered from about 6 to 100 eV. The second set covered the thermal range, the 0.3 eV resonance and up to the few eV region.

Values of relative nubar have been obtained for about twenty-two resonances as well as in the thermal region. The statistical precision varies from 0.2 to 0.5%. Significant fluctuations in nubar from resonance to resonance are observed. In addition, the relative nubar value of the 0.3 eV resonance is about 1% lower than that at 0.025 eV. For the 0.3 to 0.025 eV region, nubar shows a monotonically increasing trend.

These new results essentially agree with Weinstein's[3] results if we renormalize his data downward slightly above 45 eV. Comparisons to ORNL data[4] of our relative data have been made. There is a general similarity in shape; however, our nubar data show more of a tendency to separate into at least 2 groups. Both sets of results show a very low fluctuation in nubar at the 42 and 45 eV resonances.

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NEUTRON CAPTURE CROSS SECTIONS OF ^{105}Pd, ^{151}Eu, ^{153}Eu AND ^{103}Rh

H. D. Knox,* A. Sanislo, R. W. Hockenbury and R. C. Block

Capture measurements have been made on the above isotopes covering the region from 20 eV to about 100 keV. The primary goal of these experiments is the keV capture cross section. Linac running conditions were 550 pps and a pulse width of 66 ns. The time-dependent background was determined by using black resonance filters of S, Al, Na and Mn.

The detector efficiency will be determined from pulse-height vs. time-of-flight data for each sample. In order to obtain another normalization, transmission data have also been taken over the same energy range. The transmission measurement will thus provide a normalization as well as a check on the resonance parameters in the resolved resonance region.

Corrections for deadtime and background effects have been made to the capture and transmission data. Some multiple scattering corrections were made to some of the resolved resonances in the capture data. The Harvey-Atta code will be used to analyze the same resonances in the transmission data and a combination of the two sets of results will give a normalization for the keV capture cross section.

Since ^{151}Eu has a very large thermal capture cross section, additional calculations are being made to determine possible effects due to any moisture contamination in the sample. Special precautions were taken to avoid this during sample preparation. Also, ^{10}B liners were used to minimize any backscattering of neutrons to the Eu samples during the capture measurements.

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

H. D. Knox,* M. Costello, N. N. Kaushal, R. W. Hockenbury
and R. C. Block

Analysis of the low resolution data is partly complete. This set of data is adequate in resolution up to 20-30 keV depending on the isotope.

Higher resolution capture data has been taken on ^{61}Ni and ^{54}Fe using the greater neutron intensity available after installation of the Model 12 electron gun. This set of data covers the range 10 to 200 keV. Linac conditions were 11 ns pulse width, 500 pps and a channel width of 7.7 ns; with an overall timing resolution including moderator effect of about 0.8 ns/meter. High resolution transmission measurements are planned, to supplement the capture data.

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NEUTRON CAPTURE CROSS SECTION OF ^{242}Pu IN THE KEV ENERGY REGION

A. J. Sanislo,[*] N. N. Kaushal and R. W. Hockenbury

Preparations were made for ^{242}Pu capture cross-section measurements. Electronics were calibrated. The 1.25-meter liquid scintillation detector electronics were checked for gain shifts. The PDP-7 system was linked to this detector in a high-low bias procedure to discriminate between fission and capture events.

We plan to cover the energy range from 100 eV to about 200 keV. Information on subthreshold fission groups is expected to be obtained. Four filters will be used for time-dependent background determination.

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[*] Based in part on the Master of Science thesis of A. J. Sanislo.

RADIATIVE CAPTURE IN ^{60}Ni AND Fe IN THE THERMAL TO LOW KEV RANGE

P. H. Brown,* R. C. Block and J. R. Tatarczuk

The following is an abstract of a paper being prepared for submission to the Physical Review.

ABSTRACT

The spectrum of γ-rays given off following radiative neutron capture in ^{60}Ni and Fe has been studied as a function of neutron energy. The RPI LINAC is used as the neutron source and the neutron energy is determined by the time-of-flight method (with a resolution of 8 nsec/m) using a lithium-drifted germanium (Ge(Li)) detector. The γ-ray resolution obtained with the Ge(Li) detector is 12 keV full-width at half-maximum (FWHM) for an 8 MeV γ-ray and 4 keV FWHM for a 1 MeV γ-ray. The intensities of prominent γ-rays in the ^{60}Ni and Fe capture spectrum were measured as a function of neutron energy from thermal to low keV neutron energies. In addition the partial capture cross sections for these prominent γ-rays were measured in the low eV to low keV neutron energy range. The results, which show a dominance of the spectrum by only a few high energy γ-rays, are discussed in terms of the experimental observables due to compound nucleus (statistical) capture and single-particle (non-statistical) capture.

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*Based in part on the Ph.D. thesis of P. H. Brown.

NATURAL Ni(n,γ) AND ^{54}Fe(n,γ) SPECTRA DATA ACQUISITION

S. E. Arendt,* E. J. Winhold and R. C. Block

Using the RPI LINAC and the PDP-9 data acquisition system,[1] an experiment was performed to determine the spectrum of emitted gamma rays as a function of neutron energy following neutron capture in natural nickel (approx. 430 gms.) and a separated ^{54}Fe isotope (approx. 65 gms.). The experimental details parallel those for the ^{60}Ni experiment reported in a previous Progress Report.[2]

The natural nickel data accumulation required 60 hours of linac time with linac beam parameters as follows: width 11 nsec, repetition rate 550 Hz, and average current 36 μA. The ^{54}Fe data accumulation required 45 hours of linac time with linac beam parameters as follows: width 66 nsec, repetition rate 500 Hz, and average current 135 μA. For both samples 38 neutron time-of-flight regions were obtained each containing 4096 channels of gamma ray pulse height data.

Data on ^{52}Cr will next be obtained and analysis on all three samples will be forthcoming.

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*Based in part on the Ph.D. thesis of S. E. Arendt.

3905

DIFFERENTIAL ELASTIC SCATTERING CROSS SECTIONS OF KEV NEUTRONS FROM IRON AND NICKEL

R. Zuhr* and K. Min

Final analysis of the six angle differential elastic scattering data for natural iron and nickel has been completed. As previously reported,[1,2] these measurements were made relative to a lead standard at angles from 30 to 150°. Time-of-flight methods, using the RPI LINAC as a pulsed neutron source, gave energy resolution of 3 nanoseconds per meter throughout the desired energy range of 10 to 650 kilovolts.

A revised method of background determination was employed in this analysis. It is a phenomenological approach based upon the assumption that the background is made up of the following contributions.

1) Sample and time independent. (Constant or steady-state background.)
2) Sample independent, time dependent. (Neutrons and gamma rays from the LINAC which are scattered into the detector by material other than the sample.)
3) Sample and time dependent. (Primarily gamma rays scattered by the sample into the detector, with some multiply scattered neutrons.)

Each of these sources was determined experimentally, where possible, and subtracted from the raw data. The accuracy of these assumptions is born out by the consistency of our results.

All the cross sections were corrected for multiple scattering, which is appreciable because of our use of relatively thick samples, by using the method of Lane and Miller.[3] This is a combined Analytic-Monte Carlo approach which includes scattering through fourth order.

Finally the data were fitted with Legendre Polynomial expansions.

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

$$\sigma_s(\theta) = \sum_{\ell=0}^{4} A\ell P\ell[\cos(\theta)]$$

Figures 1 and 2 show typical plots of differential cross section vs. cos(θ) for iron. Statistical errors are smaller than the vertical lines of the data points, while the solid curves represent second order Legendre fits. The increase in anisotropy is clear, with the largest A1 and A2 terms occurring at 400 keV.

A summary of our results is given in Figs. 3 through 8. Figures 3 through 5 show W1, W2 and W3 for natural iron, where:

$$W_\ell = A\ell/A0$$

W1 is thus a relative measure of s- p-wave interference, W2 is a measure of p-wave scattering with the possibility of higher order interference, and W3 is a measure of p- d-wave interference, again with the unlikely possibility of higher order interference at these low energies. The error bars represent the error of the standard sample and our statistics, as well as an estimate of the uncertainty introduced by the multiple scattering corrections. Figures 6 through 8 give the same information for nickel. Our data has also been processed with 50 keV energy resolution for comparison with Smith's data[4] above 300 kilovolts. In general, both data follow the same trends, with the present values of W_ℓ being somewhat lower than Smith's.

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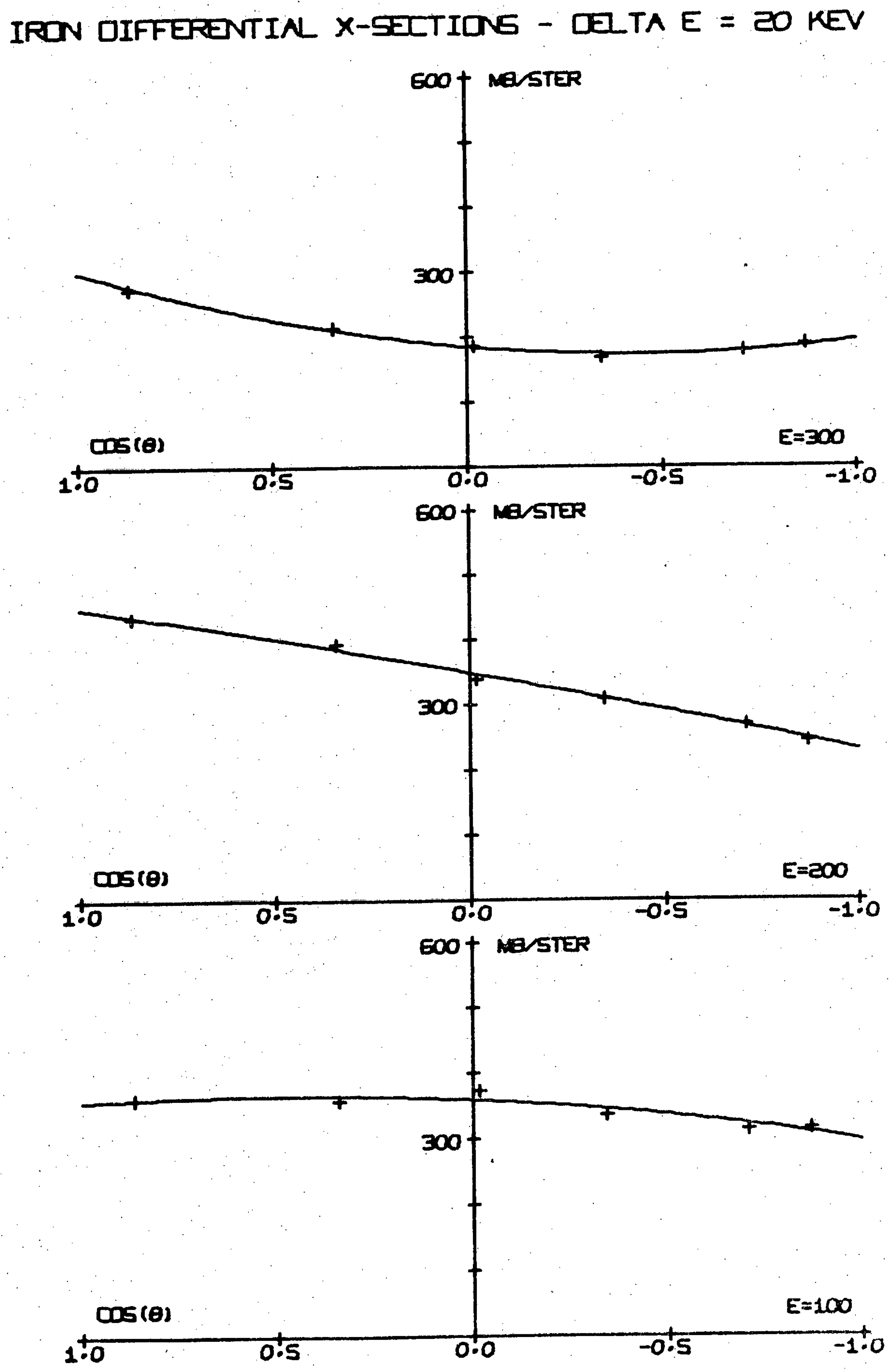

IRON DIFFERENTIAL X-SECTIONS - DELTA E = 20 KEV
600
MB/STER
300
COS(θ)
E=300
1·0
0·5
0·0
-0·5
-1·0
600
MB/STER
300
COS(θ)
E=200
1·0
0·5
0·0
-0·5
-1·0
600
MB/STER
300
COS(θ)
E=100
1·0
0·5
0·0
-0·5
-1·0

Figure 1

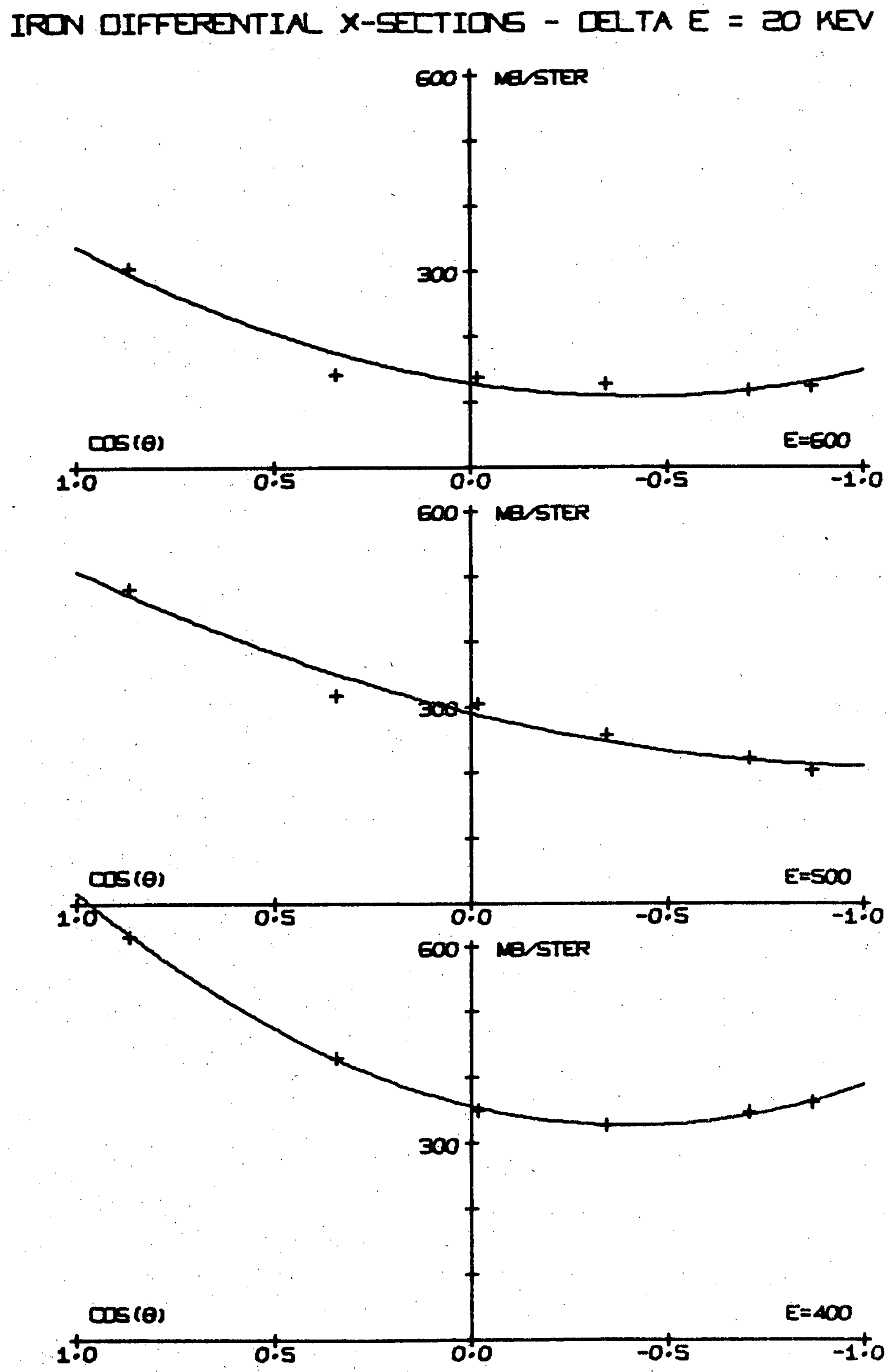

IRON DIFFERENTIAL X-SECTIONS - DELTA E = 20 KEV
600
MB/STER
300
COS(θ)
E=600
1·0
0·5
0·0
-0·5
-1·0
600
MB/STER
300
COS(θ)
E=500
1·0
0·5
0·0
-0·5
-1·0
600
MB/STER
300
COS(θ)
E=400
1·0
0·5
0·0
-0·5
-1·0

Figure 2

Figure 3

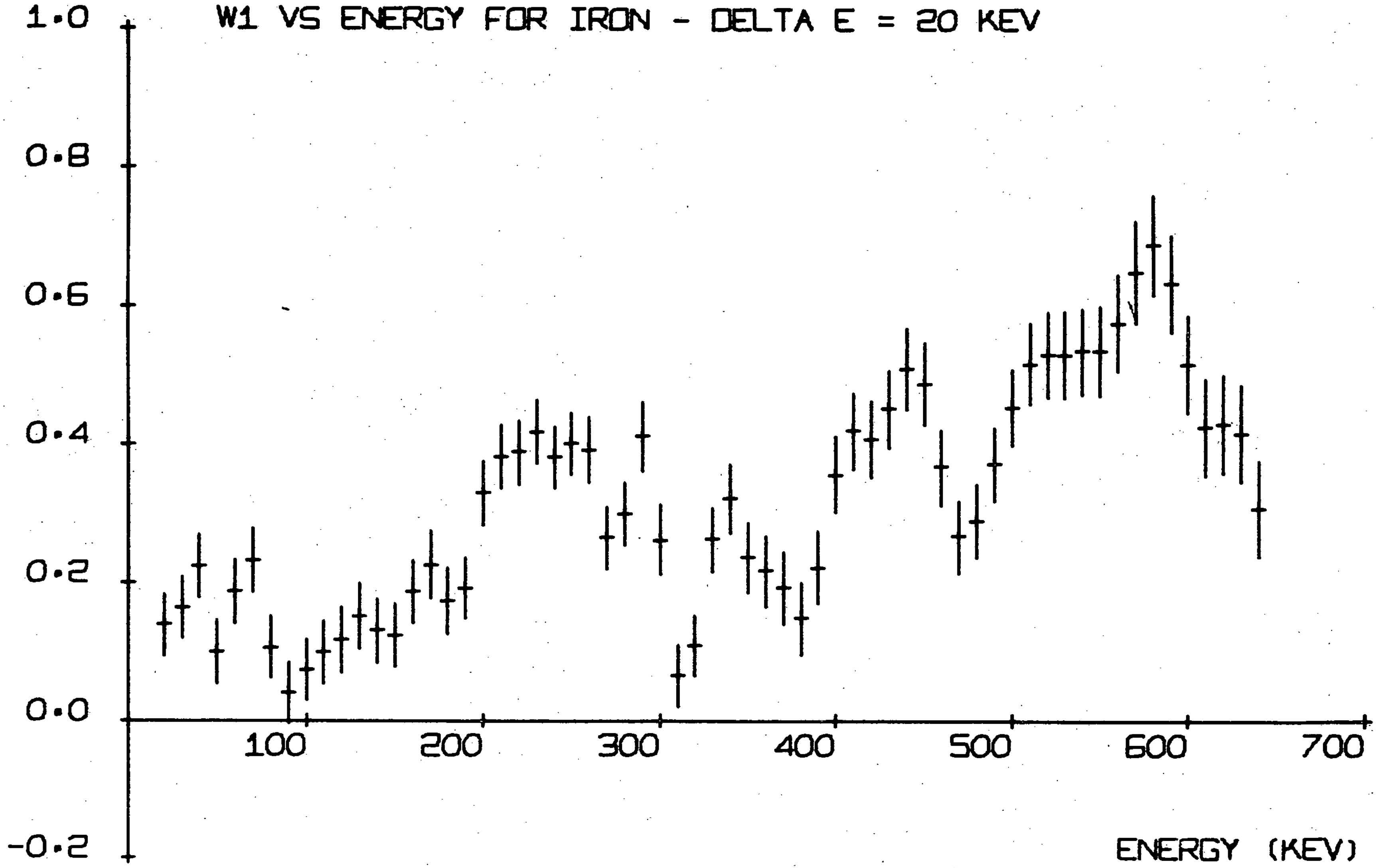

W1 VS ENERGY FOR IRON - DELTA E = 20 KEV
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
100
200
300
400
500
600
700
ENERGY (KEV)

Figure 4

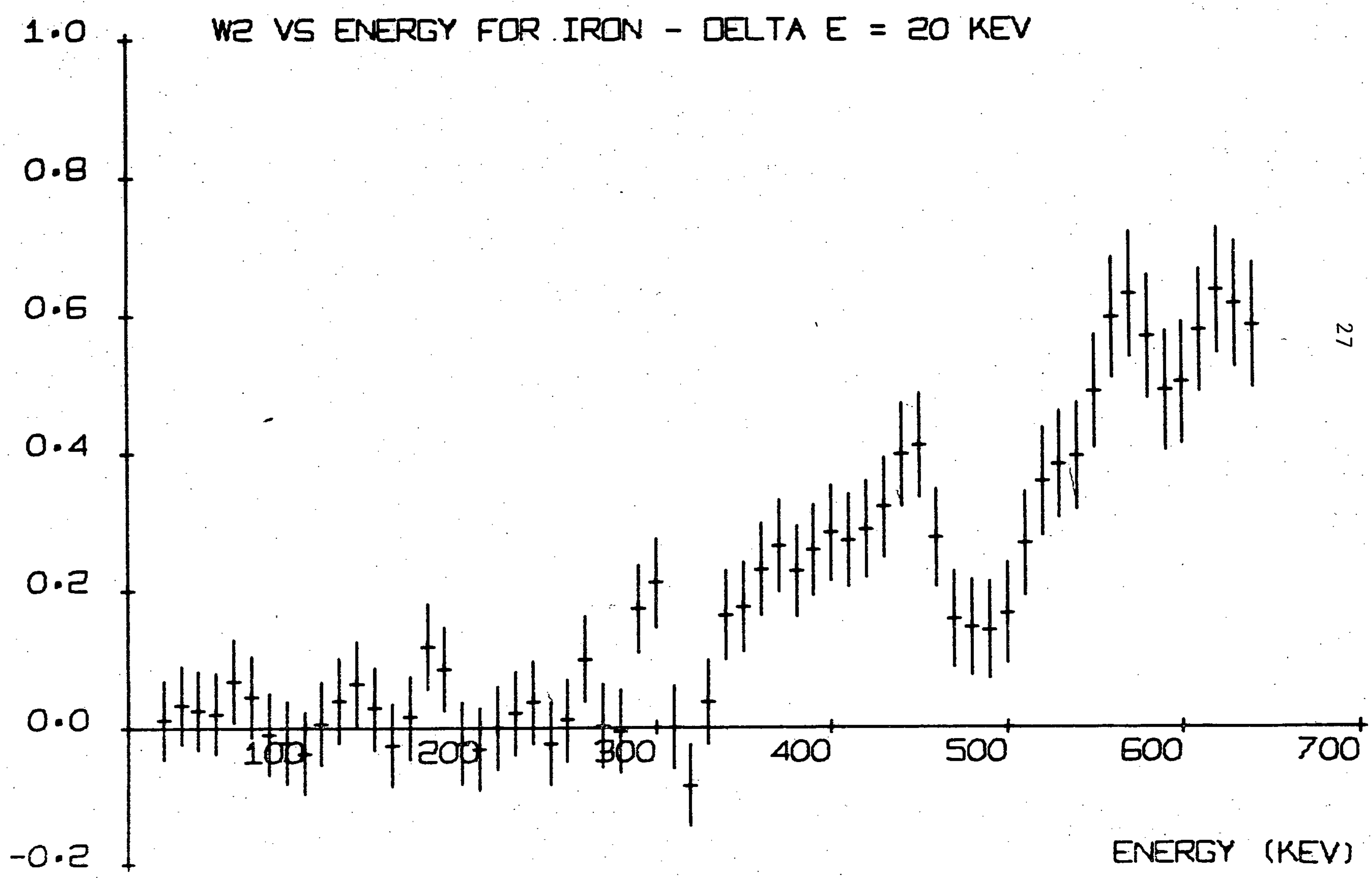

W2 VS ENERGY FOR IRON - DELTA E = 20 KEV
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
100
200
300
400
500
600
700
ENERGY (KEV)

Figure 5

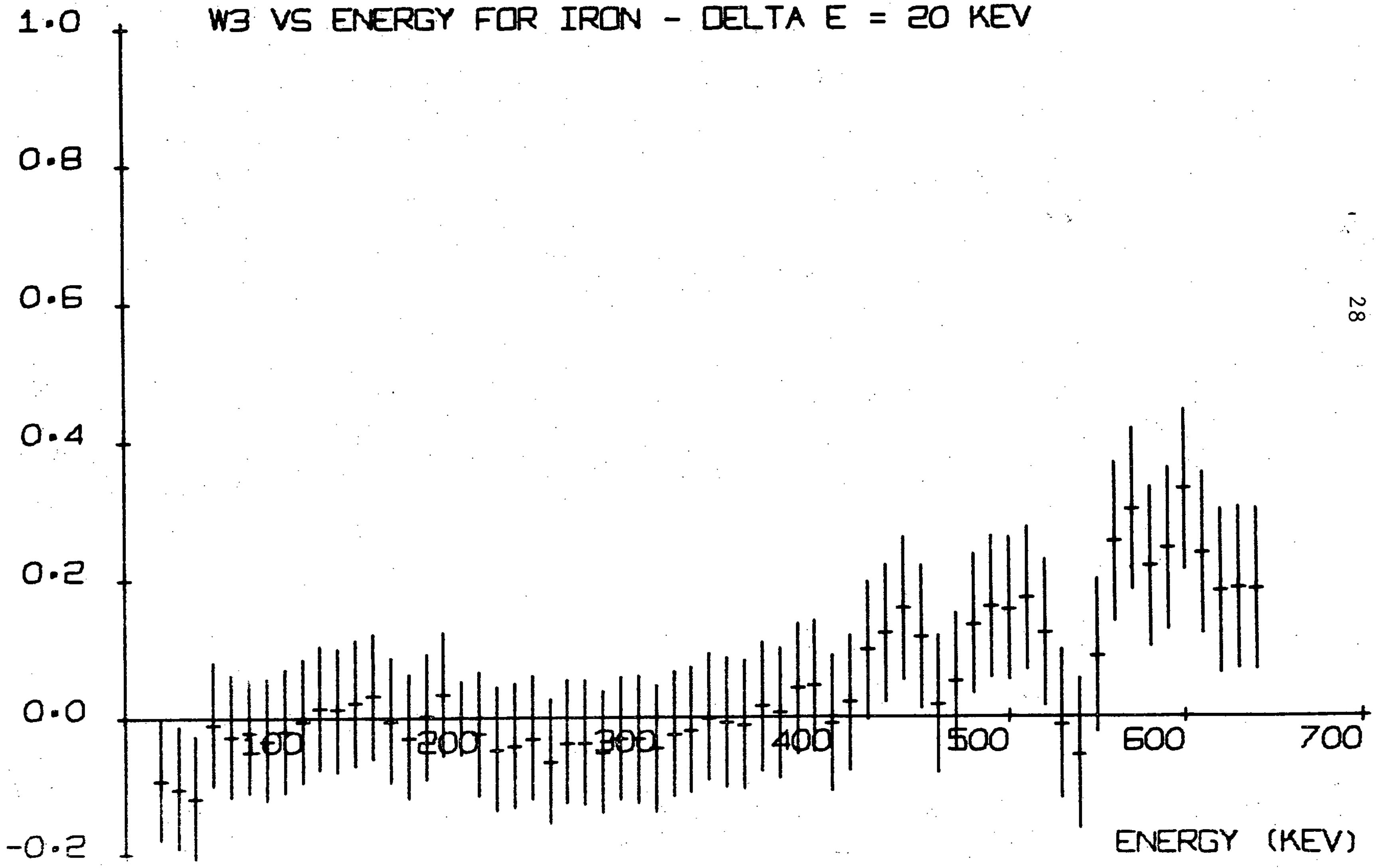

W3 VS ENERGY FOR IRON - DELTA E = 20 KEV
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
100
200
300
400
500
600
700
ENERGY (KEV)

Figure 6

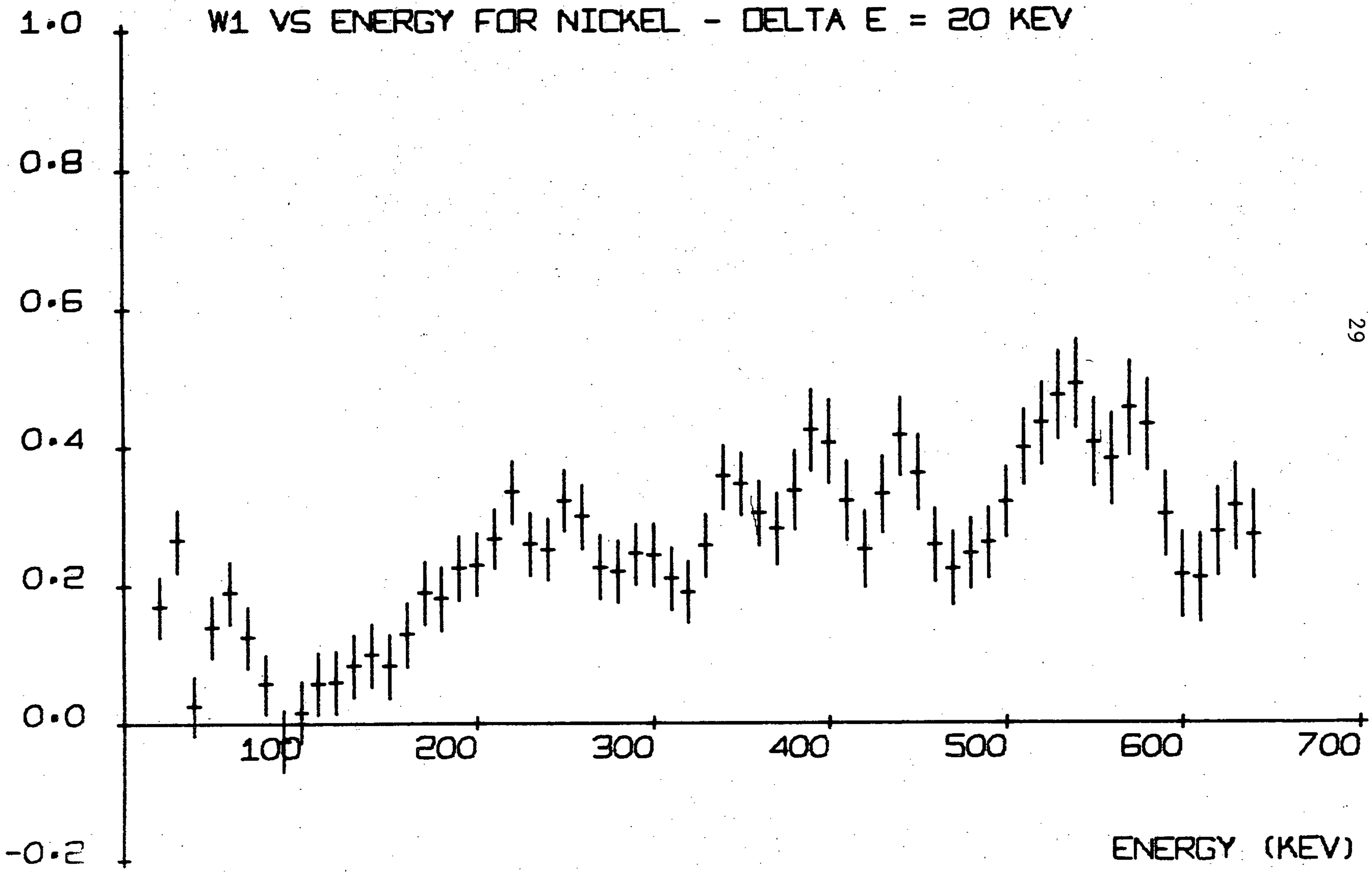

W1 VS ENERGY FOR NICKEL - DELTA E = 20 KEV
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
100
200
300
400
500
600
700
ENERGY (KEV)

Figure 7

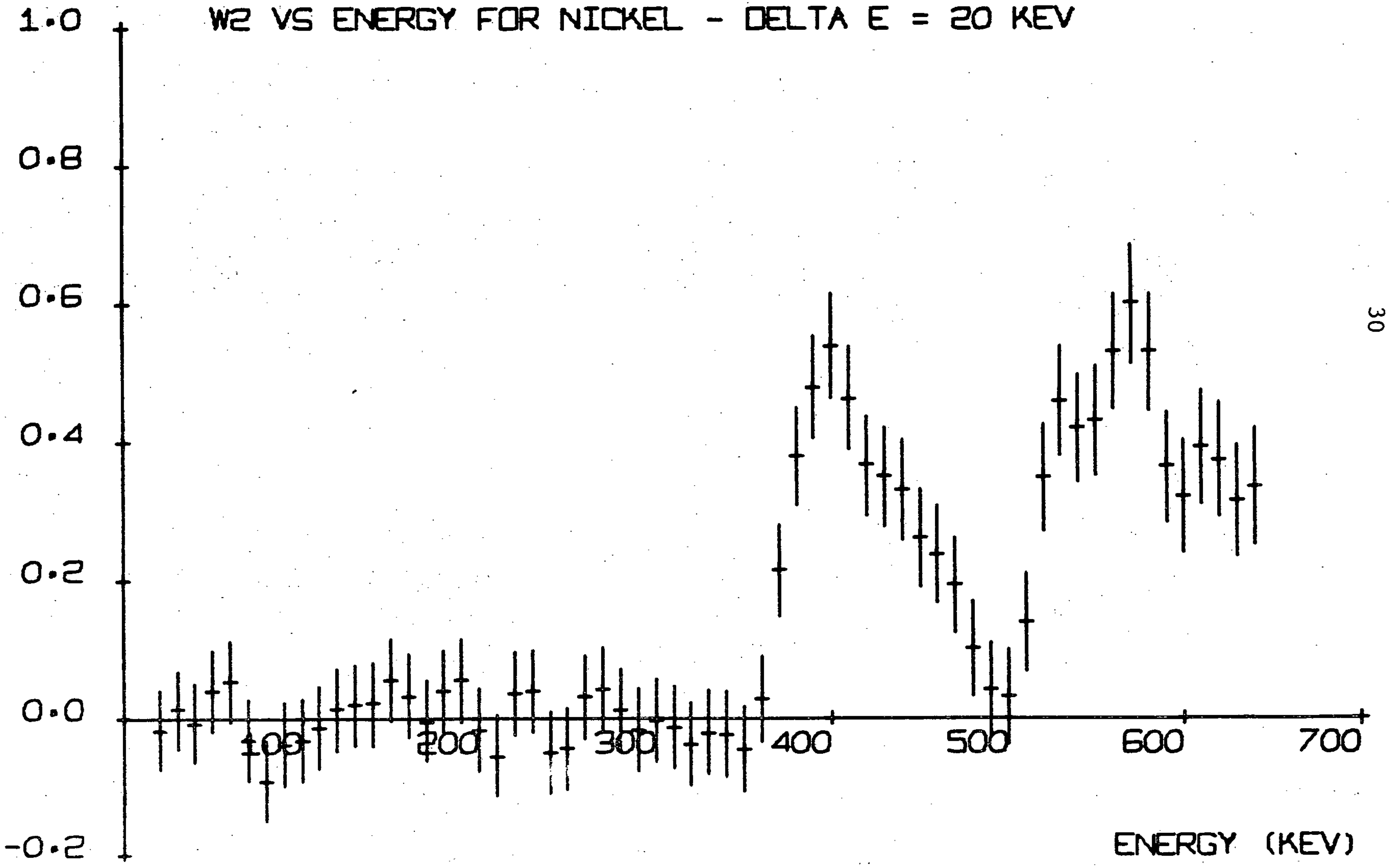
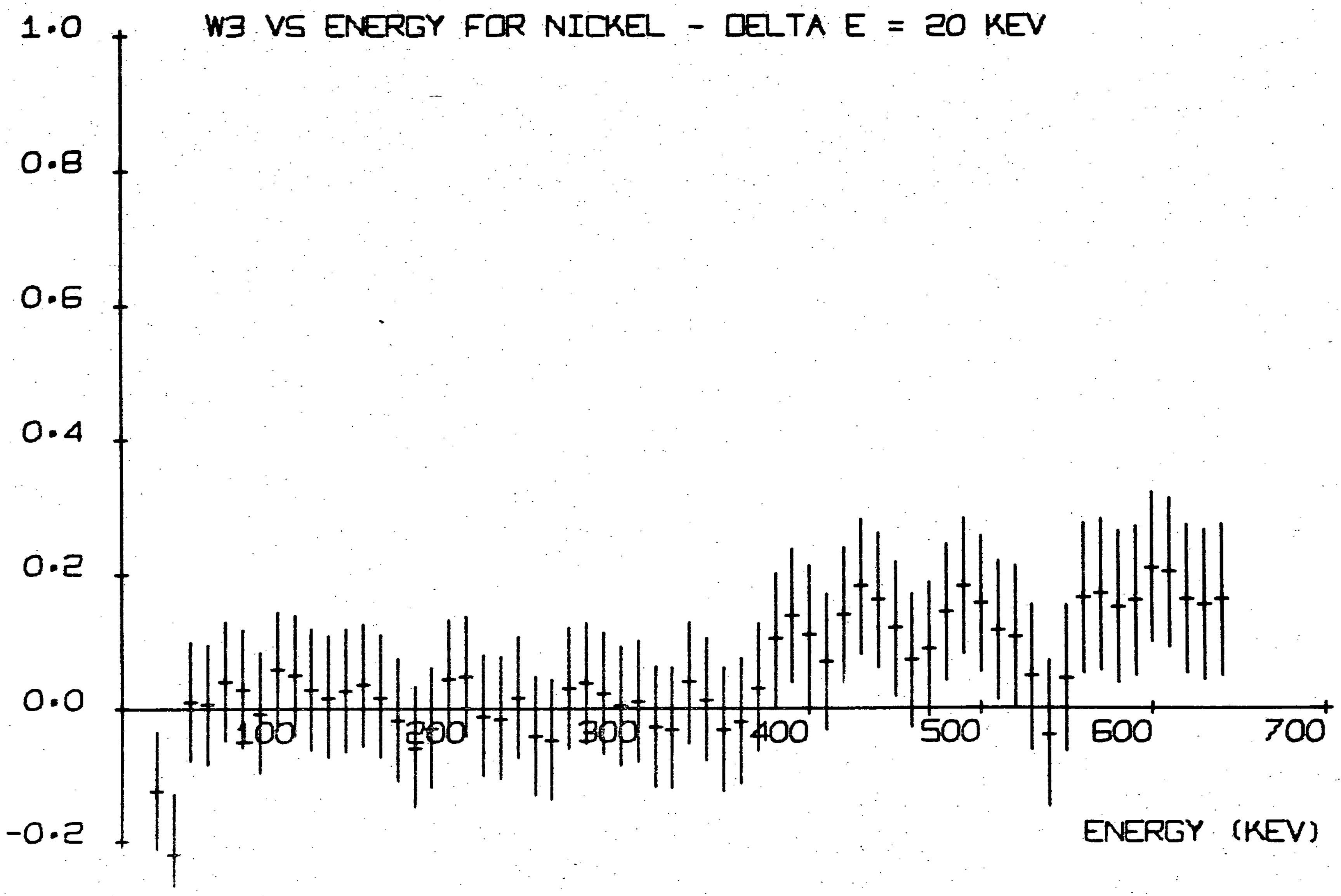

W2 VS ENERGY FOR NICKEL - DELTA E = 20 KEV
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
100
200
300
400
500
600
700
ENERGY (KEV)

Figure 8


W3 VS ENERGY FOR NICKEL - DELTA E = 20 KEV
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
100
200
300
400
500
600
700
ENERGY (KEV)

TOTAL NEUTRON CROSS SECTION OF ^{235}U

F. L. Green,* K. A. Nadolny and P. Stoler

The total neutron cross section of ^{235}U was determined from 0.5 to about 30 MeV using a proton-recoil scintillator on the 250-meter flight path.

Between 0.7 and 10 MeV, the present data have a statistical error of ±1% and are in agreement, within the error (1%), of Heaton and Schwartz[1] and also with the data of Glasgow and Foster.[2]

The results of Smith and Whalen[3] from about 0.7 to 1.4 MeV lie slightly lower (about 1½%) than the present results.

REFERENCES:

1. R. B. Schwartz, private communication.
2. D. W. Glasgow and D. G. Foster, Phys. Rev. 3, 604 (1971).
3. National Neutron Cross Section Center, private communication.

*Based in part on the B.S. thesis of F. L. Green.

TOTAL NEUTRON CROSS SECTION OF ^{239}Pu

K. A. Nadolny,* F. L. Green and P. Stoler

Transmission measurements were made on ^{239}Pu from 0.5 to 30 MeV. A proton-recoil liquid scintillation detector was used at the 250-meter flight path. Linac running conditions were: (1) pulse width of 20 ns and (2) 500 pps repetition rate.

The results have been compared to those of Ref. 1. The agreement is within statistical errors in the range 1-15 MeV. Between 0.5 and about 1.4 MeV, the data of Ref. 2 lie above the present data but the difference is within the statistical errors of the measurements.

REFERENCES:

1. D. G. Foster and D. W. Glasgow, Phys. Rev. 3, 576 (1971).
2. National Neutron Cross Section Center, private communication.

*Based in part on the B.S. thesis of K. A. Nadolny.

CORRELATIONS BETWEEN REDUCED NEUTRON AND RADIATIVE WIDTHS IN NEUTRON RESONANCES

M. Lubert,* R. C. Block and N. C. Francis

The cross section measurements conducted at the RPI LINAC with the chromium and nickel isotopes showed strong correlations between the reduced neutron and total radiative widths.[1] Further, the ^{60}Ni capture cross section below the 12.4 keV resonance displayed a significant slowly varying cross section of approximately 50 mb.

These phenomena were investigated with a capture model which includes both channel and compound contributions to the cross section. This is similar to the nuclear model formulated by Lane and Lynn.[2] The nuclear reaction model is one of an s-wave neutron coupled to the core of the target nucleus which undergoes an E1 transition to a low-lying single particle state without forming a compound nucleus. The theory was developed in terms of R-matrix theory by considering the external region of configuration space to coincide with the channel region. The dipole matrix element was evaluated using R-matrix phase shifts to define the final continuum states. The resonance parameters were consistent with the neutron total cross section measurements at RPI.[1] The basic partial radiative width data for ^{53}Cr and ^{61}Ni was obtained from the photothreshold experiments of Baglan[3] and Jackson.[4]

^{53}Cr (γ,n) Analysis

The $3/2^-$ ground state makes a transition to the $\frac{1}{2}^+$ final positive energy neutron state. The neutron reduced width for the ^{53}Cr lowest energy bound state was obtained by fitting the line shape reported by Jackson below the 92 keV level. The reduced width factor, $\theta_o^2 = 0.35$, for the ^{53}Cr target nucleus bound state was derived with the single particle state normalized to unity for the region outside the nuclear surface. The partial channel

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*Based in part on the Ph.D. thesis of M. Lubert.

radiative width, $\Gamma_{\gamma o}^{ch}$, for each resonance was calculated from the theoretical channel cross section. The experimental partial widths, $\Gamma_{\gamma o}$, were obtained by adding the channel and compound nucleus amplitudes and squaring.

$$\Gamma_{\gamma o} = (\sqrt{\Gamma_{\gamma o}^{ch}} + \sqrt{\Gamma_{\gamma o}^{cn}})^2$$

$\Gamma_{\gamma o}^{cn}$ is the partial compound nucleus width which is obtained from this equation. The thermal neutron capture cross section of ^{52}Cr for ground state transitions was obtained from the (γ,n) analysis using detailed balance. The experimental thermal (n,γ) cross section was multiplied by a measured ground state branching ratio[5] to yield 0.55b. The theoretical value was 0.53b. Negative energy state compound nucleus contributions were neglected in view of the fact that none were necessary for the total cross section calculation. In addition, the 50.2 keV resonance compound nucleus contribution to the ground state does not add significantly to the thermal (n,γ) cross section.

As a further test of the model and its parameters, the calculated total radiative widths for the 50.2 and 97.1 keV resonances were compared to experiment.[1] The theoretical total widths were obtained from the separate channel and compound nucleus components. The channel-compound nucleus interference part was neglected since their sum is expected to be small due to the random sign of the compound nucleus amplitude. The ground state channel capture width was determined from the ^{53}Cr(γ,n) calculation. The total channel capture width was determined using the thermal neutron ground state transition branching ratio. The compound nucleus part of the cross section for the excited state transitions was estimated by using the average compound nucleus width from the ^{53}Cr (γ,n) analysis. The photon energy cubed dipole law was assumed. The measured Γ_{γ}^{exp} and calculated widths $\Gamma_{\gamma}^{cal'd}$ are shown in Table 1.

Table 1. Calculated and Measured ^{52}Cr Total Radiative Widths

E_o(keV)	Γ_γ^{exp}(eV)	$\Gamma_\gamma^{cal'd}$(eV)
50.2	1.16	1.49
97.1	4.80	3.70

^{61}Ni Analysis

Similar results have been obtained for the ^{61}Ni (γ,n) and the ^{60}Ni (n,γ) reactions. The reduced width, $\theta_o^2 = 0.17$, was obtained from fitting Jackson's experimental data. These are summarized in Table 2.

Table 2. Calculated and Measured ^{60}Ni Total Radiative Widths

E_o(keV)	Γ_γ^{exp}(eV)	$\Gamma_\gamma^{cal'd}$(eV)
12.5	3.3	3.6
28.6	1.6	1.1

The calculated thermal ^{60}Ni (n,γ) cross section of 1.2b compares well with the 1.1b reported in BNL-325. The RPI measurements for ^{60}Ni (n,γ) reported an asymmetry in the 12.5 keV line shape. The measured cross section, which exhibits constructive interference below the resonance, is 50 mb at about 5 keV. The calculated cross section displays a similar line shape and a cross section of 20 mb at 5 keV.

The analysis of the (n,γ) and (γ,n) experiments indicate: (1) The absence of (γ,n) experimental correlations between the $\Gamma_{\gamma o}$ and Γ_n^o is due to two factors. First, this correlation is reduced by the random compound nucleus partial radiative amplitude which adds coherently to the channel amplitude. Second, the experimental correlation may be reduced because of experimental error. The (γ,n) experiments are difficult to perform and subject to area and background uncertainties; (2) The correlations observed at RPI between the reduced neutron and total radiative widths for the nickel and chromium isotopes can be interpreted as due to correlations between partial radiative and reduced neutron widths for several final states where the interference between the channel and compound nucleus has cancelled. This indicates non-statistical effects such as channel capture are important in the radiative process; (3) The resonance line shapes determined by the theory are asymmetric. This characteristic shape is expected when the channel width is greater than the compound nucleus contribution; (4) If one has measured the partial cross section to some final state for an isotope, this analysis can determine the reduced width. This provides another method, besides the (d,p) reaction, for calculating the reduced width; (5) The channel cross section shapes differ from the Breit-Wigner theory. In particular, the channel cross section below the resonance energy is greater than the Breit-Wigner cross section. As neutrons diffuse through materials such as iron, the neutron flux is depressed at the resonance and is large at the total cross section minima positions. At these latter energies, the difference between the channel and compound nucleus cross section is large and the channel reaction rate can be significant.

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REACTOR PHYSICS AND ENGINEERING - EXPERIMENTAL

REACTOR PHYSICS AND ENGINEERING - EXPERIMENTAL

The major activity during the past year has been the measurement and analysis of fast- and intermediate-energy neutron spectra in metallic sodium at room temperature. Using a newly constructed oil-cooled target, the time-of-flight measurements were extended down to low energies (10 eV) and the group cross section sets and calculated spectra have also been correspondingly generated to cover the entire energy range from 10 eV to 10 MeV. The primary phase of these integral measurements on sodium and the first assessment of sodium cross section data has been completed. Position-dependent spectrum measurements from several different points in the sodium assembly have been compared with calculations based on the one-dimensional S_N code DTF-IV, using 49 groups, P_8 scattering and P_{15} asymmetric quadrature. The two data files ENDF/B-I and ENDF/B-III have been examined in the analysis to date. A comprehensive paper[1] on the measurement and analysis of fast neutron spectra in sodium is being prepared for publication.

Continuing effort was devoted to updating the analysis of earlier integral measurements and data file assessments. The results for iron now include the assessment of the file ORNL-1124. A paper[2] relating to some of the additional results was presented at the Fourth International Conference on Reactor Shielding in Paris, France in October 1972. The first phase of the analysis of preliminary spectrum measurements in a two-region system was also completed and a report[3] on this work is being submitted for publication.

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1. A. N. Mallen, N. N. Kaushal, B. K. Malaviya and E. R. Gaerttner, "Measurements and Analysis of Fast and Intermediate Energy Neutron Spectra in Metallic Sodium," to be published.
2. B. K. Malaviya, N. N. Kaushal, M. Becker, A. Ginsberg, E. Burns and E. R. Gaerttner, "Evaluation of Nuclear Data and Computational Methods for Iron as a Shield Material," Proc. of 4th Conf. on Reactor Shielding, Paris, France, October 1972.
3. D. C. Gibbs, B. K. Malaviya, N. N. Kaushal, "Experimental and Analytical Studies of Fast Neutron Transport Across a Material Interface," to be published.

MEASUREMENT AND ANALYSIS OF FAST AND INTERMEDIATE NEUTRON SPECTRA IN A SODIUM ASSEMBLY

3920

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

Measurements of neutron spectra in a sodium assembly were completed during the period of this annual report. A schematic diagram of the assembly is shown in Fig. 1. Measurements were made at several different angles for radial positions of 10.5, 18.5, 26.5 and 34.5 inches from the source. Two separate neutron sources were used in the course of these measurements. The first was an air-cooled Ta-Pb target[1,2], and the second was an oil-cooled Ta-Pb target[3] capable of handling large (5000 watts) linac beam powers. The spectrum of the oil-cooled target is significantly different from the spectrum of the air-cooled target. This necessitates separate calculational analyses of the data taken with the two different targets. The introduction of the high power oil-cooled target in the sodium was necessary, despite the additional effort required for analysis, because of low neutron intensities encountered with the low power air-cooled target. Additionally, the oil-cooled target provides a large increase in low energy neutrons (due to slowing down in the hydrogenous coolant), thus permitting a more thorough examination of the principal sodium resonance at 2.85 keV, and extending the range of fast spectra measurements downward in energy from 10 keV to 10 eV.

Calculations have been performed using the one-dimensional S_N Code DTF-IV[4] for the air-cooled target, using 49 groups in the energy range 10 keV to 10 MeV, P_8 scattering, the 'black absorber' model[5] and using ENDF/B-3 data. Figures 2, 3 and 4 show some comparisons of measured spectra in the forward direction ($\theta = 0^\circ$, $\mu = 1.0$), with calculated spectra (the superposed histograms) using a P_{15} asymmetric quadrature ($\theta = 3^\circ\ 20'$, $\mu = .99831$).

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*Based in part on the Ph.D. thesis of A. N. Mallen. Present address: Savannah River Laboratory, Aiken, South Carolina.

The calculation and experiment were both normalized to the source spectrum. As can be seen from the figures, the calculation and experiment agree quite well for Hole 1, 25.5" deep (R = 10.5"), and Hole 1, 17.5" deep (R = 18.5"), but deviates significantly from Hole 1, 9.5" deep (R = 26.5") most noticeably at high energies, where the fast flux is underpredicted by as much as a factor of 2. This disagreement is possibly due to the fact that the quadrature used in the calculation does not match the solid angles over which the measurements are made. This effect is particularly important for the zero degree direction because of a very rapid variation in the spectrum with angle in this direction.

The calculations have now been extended down to 10 eV in neutron energy. These calculations show that the results are somewhat sensitive to the size of the sphere which was chosen to represent the otherwise cuboidal assembly. A spherical model with outer boundary at 38.5 inches is adequate for predicting the shape of the flux at high energies (E>10 keV). Low energy fluxes are better represented with outer effective boundary at 44.5 inches. The amplitude normalization (between experiment and theory are dependent on the outer boundary used in the calculation).

Overall agreement between the theory and the experiment is found to be good. Some disagreements in case of measurements at back angles may be attributed to reentrant hole perturbation or a possible need for a redistribution of elastic-scattering. A correction for the reentrant hole perturbation would reduce the high energy disagreements in the backward direction and is the more likely source of the discrepancy.

Improvements of the ENDF/B-3 data file over the ENDF/B-1 file were noted below 2 keV and above 4 MeV. ENDF/B-3, however, was found to less accurately predict the flux than ENDF/B-1 in the energy range of 560 keV to 1.2 MeV because of an increase in the inelastic cross section in that range. A reduction in the inelastic cross section (to levels of ENDF/B-1) would improve the ENDF/B-3 set.

Further checks of these conclusions are being made and detailed report on the results is being prepared.

REFERENCES:

1. B. K. Malaviya, E. Greenspan and E. R. Gaerttner, "Development of Special Targets for Fast Neutron Spectrum Studies," *Trans. Am. Nucl. Soc.*, *11*, 24 (1968).
2. Linear Accelerator Project Annual Technical Report, October 1, 1970 - September 30, 1971, 113, COO-3058-1.
3. Linear Accelerator Project Annual Technical Report, October 1, 1971 - September 30, 1972, 89, COO-3058-27.
4. K. D. Lathrop, "DTF-IV - A Fortran IV Program for Solving the Multi-group Transport Equation with Anisotropic Scattering," Los Alamos Scientific Laboratory (1965).
5. Linear Accelerator Project Progress Report, October - December 1969, 19, RPI-328-173.

FIGURE CAPTIONS

Fig. 1	Schematic Diagram of the Sodium Assembly.
Figs. 2-4	Comparison of Measured Spectra Using the Air-cooled Ta-Pb Target, with Calculated Spectra (49 groups, P_8 scattering, P_{15} asymmetric quadrature, 'black absorber' one-dimensional model). Source normalized. Fig.(2) Hole 1, 25.5" deep (R = 10.5", μ = 1.0) Fig.(3) Hole 1, 17.5" deep (R = 18.5", μ = 1.0) Fig.(4) Hole 1, 9.5" deep (R = 26.5", μ = 1.0)

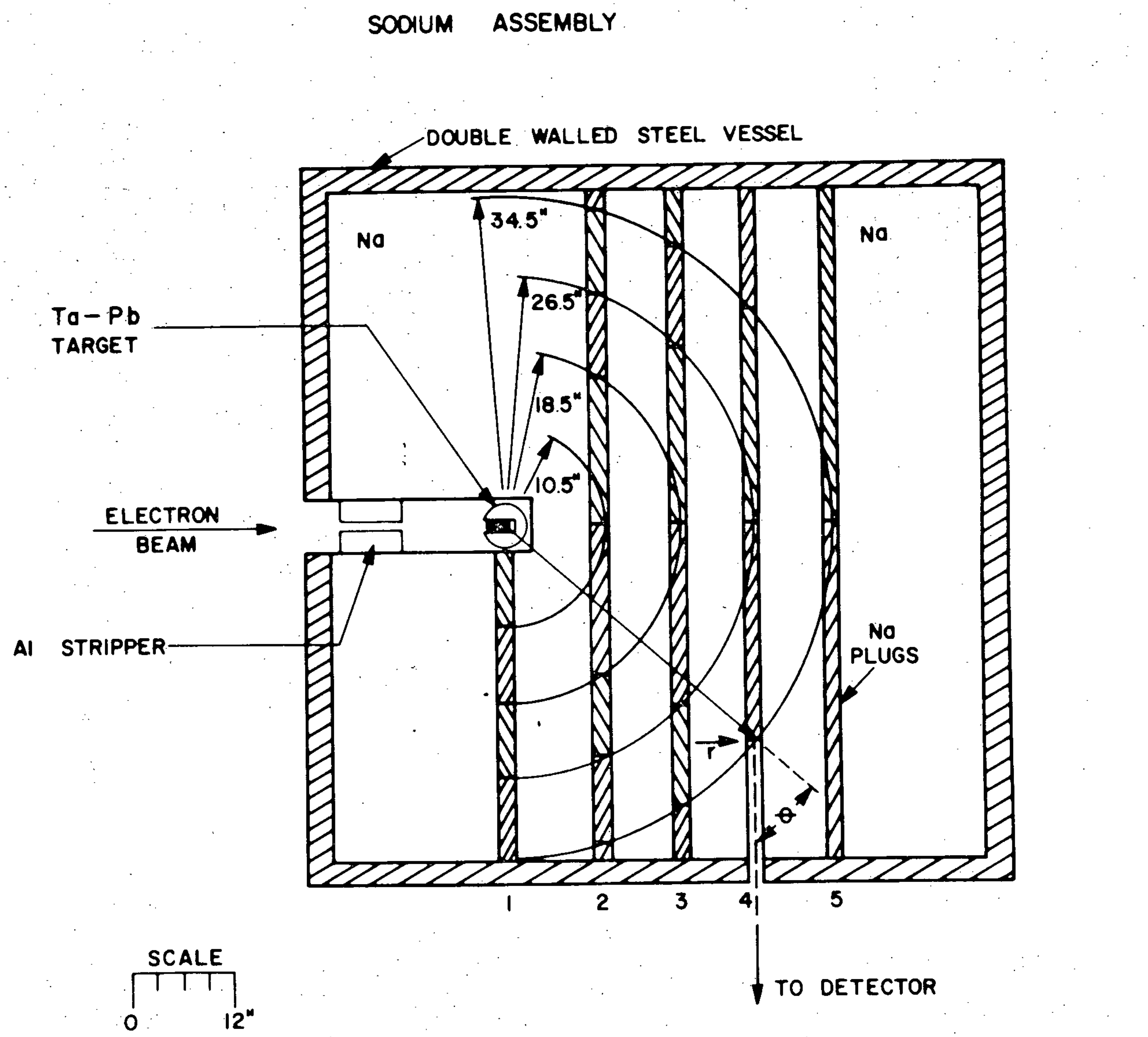
SODIUM ASSEMBLY
DOUBLE WALLED STEEL VESSEL
Na
Na
34.5"
26.5"
18.5"
10.5"
Ta - Pb
TARGET
ELECTRON
BEAM
Al STRIPPER
Na
PLUGS
r
θ
1
2
3
4
5
TO DETECTOR
SCALE
0
12"

Figure 1

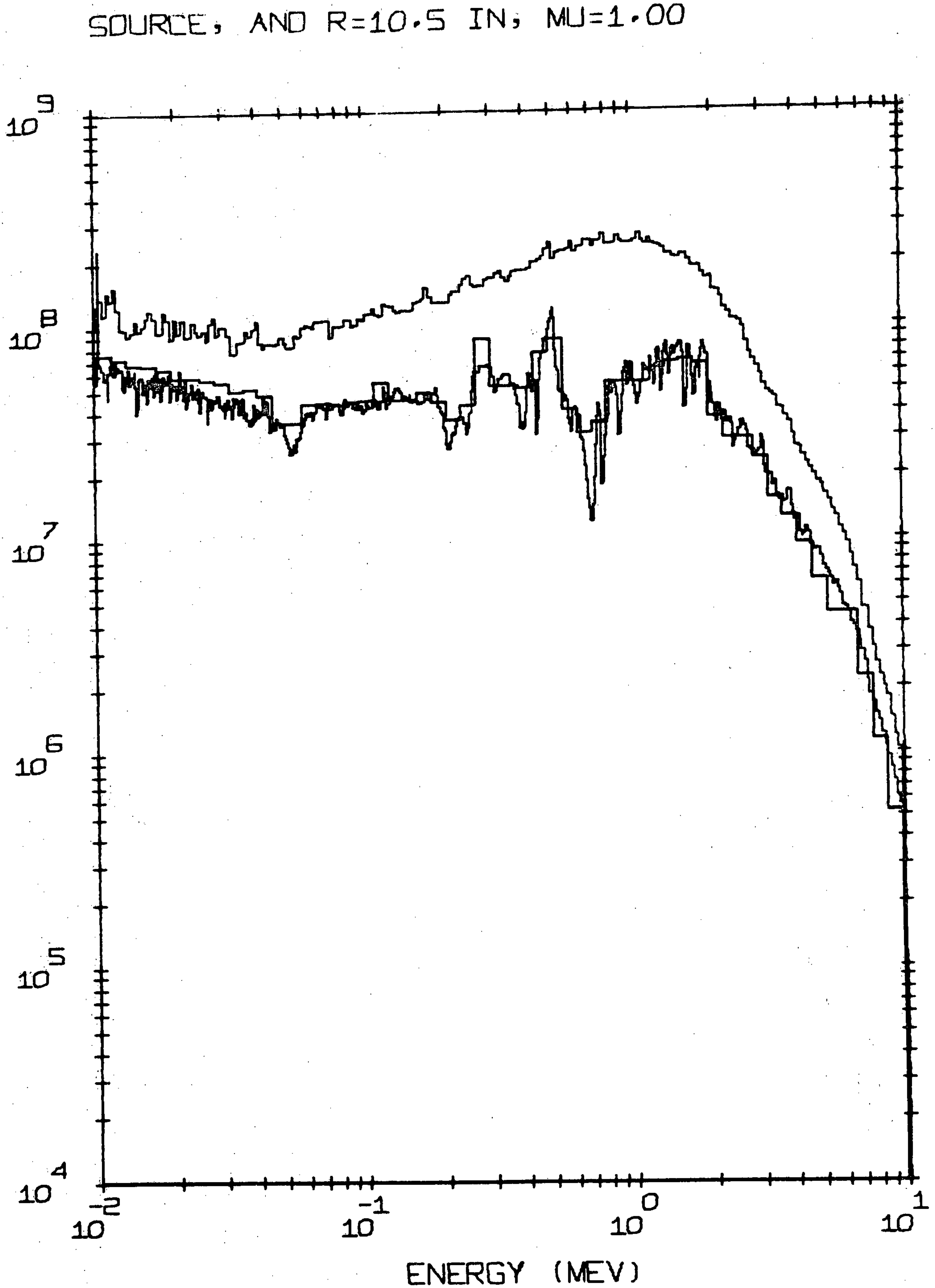
SOURCE, AND R=10.5 IN, MU=1.00
10^9
10^8
10^7
10^6
10^5
10^4
FLUX/E
10^{-2}
10^{-1}
10^0
10^1
ENERGY (MEV)

Figure 2

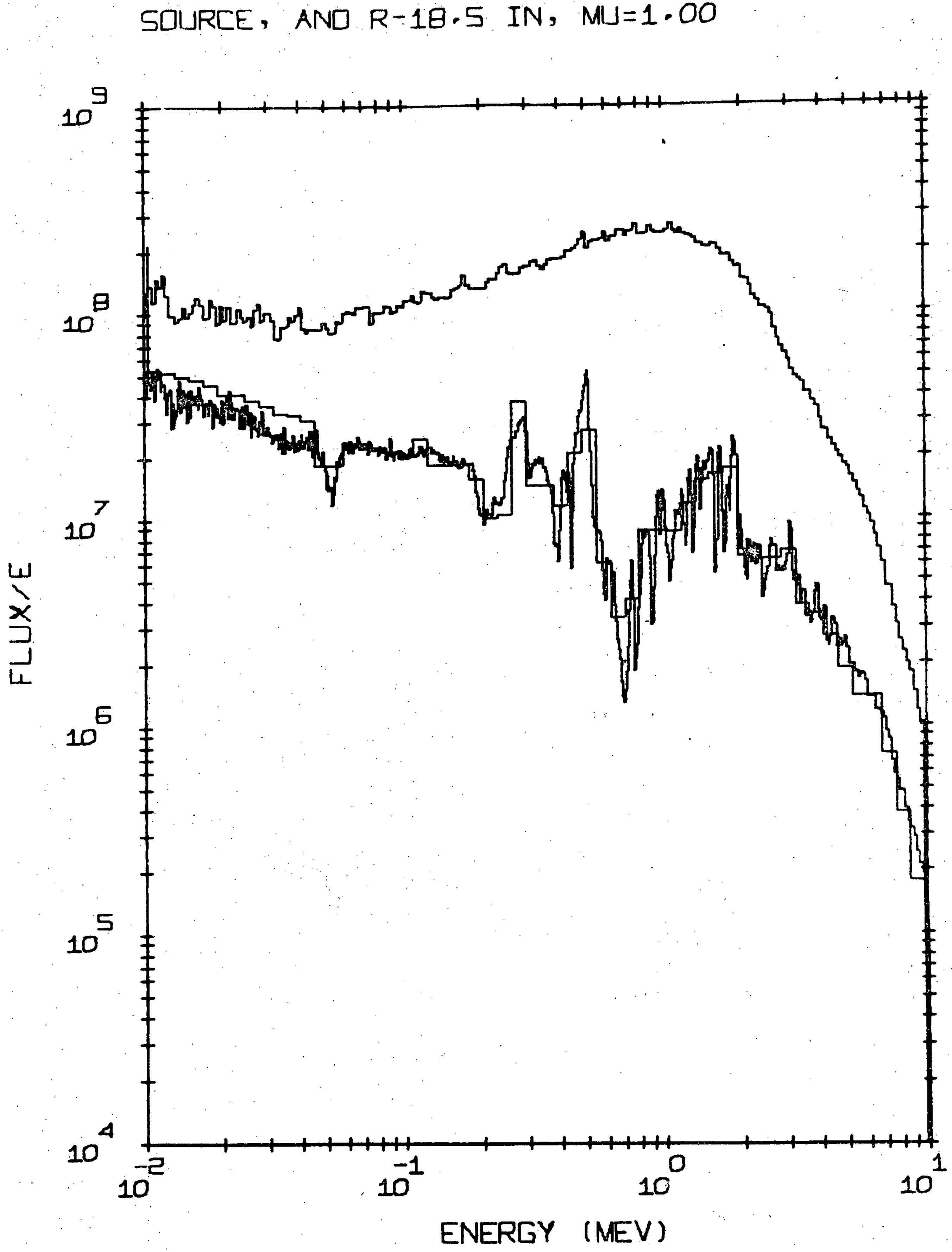
SOURCE, AND R-18.5 IN, MU=1.00
FLUX/E
10^9
10^8
10^7
10^6
10^5
10^4
10^{-2}
10^{-1}
10^0
10^1
ENERGY (MEV)

Figure 3

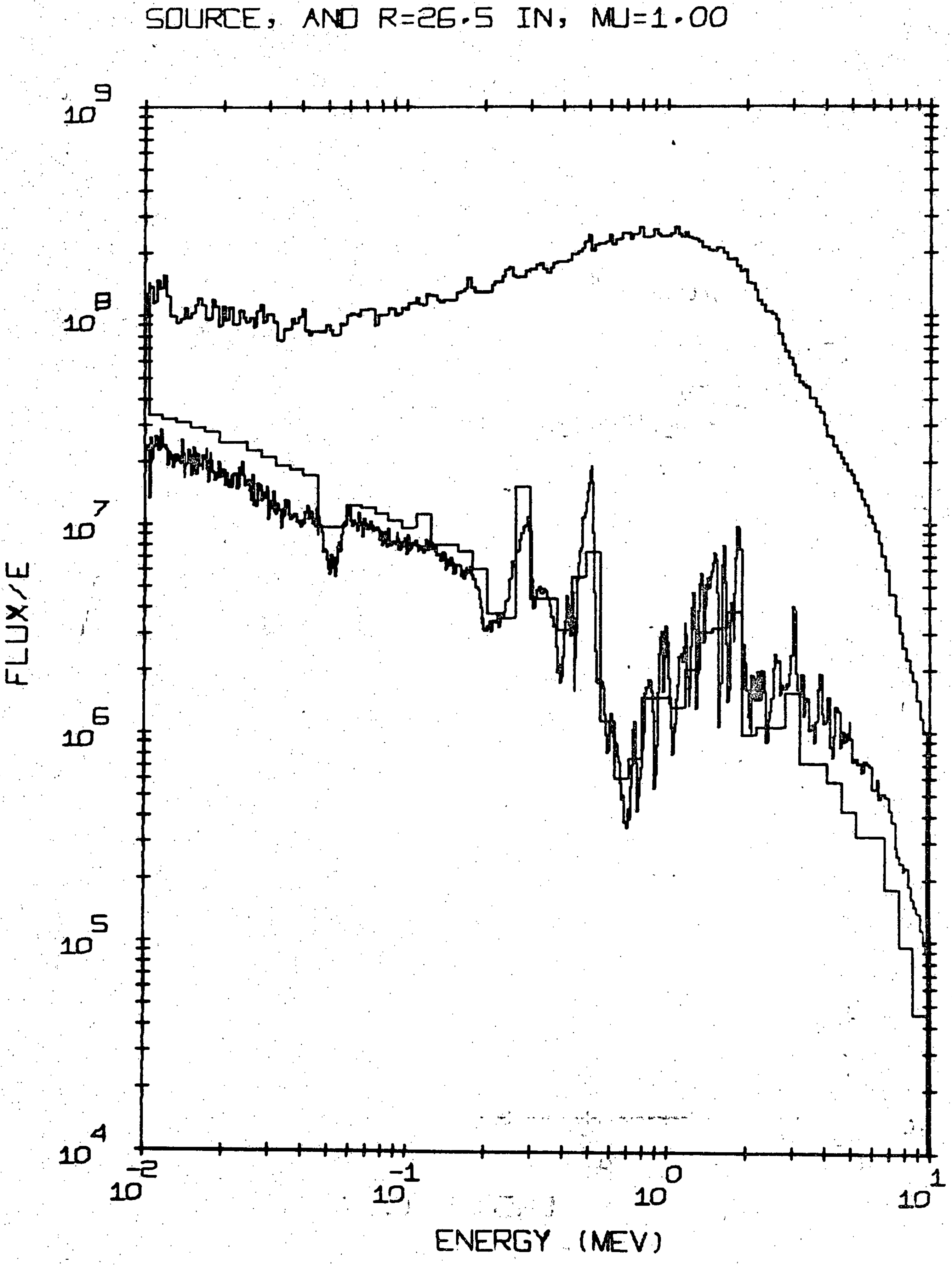
SOURCE, AND R=26.5 IN, MU=1.00
FLUX/E
10^9
10^8
10^7
10^6
10^5
10^4
10^{-2}
10^{-1}
10^0
10^1
ENERGY (MEV)

Figure 4

EVALUATION OF NUCLEAR DATA AND COMPUTATIONAL METHODS FOR IRON

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

Following is abstracted from a paper[1] entitled, "Evaluation of Nuclear Data and Computational Methods for Iron as a Shield Material," presented at the 4th International Conference on Reactor Shielding held in Paris, France, October 9-13 1972. This paper updates the previous assessments[2,3] of iron data to include the file ORNL-1124.

Experimental and analytical investigations of fast neutron transport in iron are discussed from the point of view of checking differential nuclear data useful in reactor shielding. Time-of-flight measured fast neutron angular flux spectra from different positions and directions in a clean, homogeneous iron assembly are analyzed using multigroup transport calculations, continuous slowing down theory and differential data from standard files as input to the calculations. A critical assessment of cross-section data files for iron is presented.

Several data files have been used to try to predict measured spectra in 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 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. There have been new measurements of the 27 keV resonance, and these measurements are expected to influence ENDF/B-III and other new files.

REFERENCES:

1. B. K. Malaviya, N. N. Kaushal, M. Becker, A. Ginsberg, E. Burns and E. R. Gaerttner, "Evaluation of Nuclear Data and Computational Methods for Iron as a Shield Material," Proceedings of the Fourth International Conference on Reactor Shielding, Paris, France, October 9-13 1972 (in press).
2. B. K. Malaviya, N. N. Kaushal, M. Becker, A. Ginsberg, E. Burns and E. R. Gaerttner, "Integral Tests and Evaluation of Cross Section Data from Studies of Fast Neutron Transport in Bulk Media," Proc. of the Third Conf. on Neutron Cross Sections and Technology, March 1971, Knoxville, Tennessee, Vol. I, p. 91 (1971).
3. B. K. Malaviya, N. N. Kaushal, M. Becker, A. Ginsberg, E. Burns and E. R. Gaerttner, "Experimental and Analytical Studies of Fast Neutron Transport in Iron," Nucl. Sci. Eng. 47, 329-348 (1972).

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.

Effort has been oriented to account for three objectives over the time period (to end June 30, 1974) in which the current mode of operation of RRD-sponsored research is to be terminated. First, activities currently in progress are being completed, with particular emphasis on student projects. Second, these activities are being oriented to the extent possible to provide for a smooth transition to what are anticipated to be the new AEC research interests at RPI beginning in FY 1975. Third, documentation of results under the existing LINAC Project are to be completed. Emphasis has been placed on the first of the three objectives so far, and increased emphasis on the other two will be evident in the coming year.

REACTOR THEORY AND ANALYSIS

M. Becker, M. Danchak,* G. Epstein* and S. Kang

Analysis of spectra in depleted uranium has been performed using several data files. Analyses of spectra with ENDF/B-III data led to experiment-theory discrepancies. Comparable to those observed with earlier ENDF/B files, and comparable to those observed in Germany where KEDAK file data were used.[1] Thus, recommendations made in regard to earlier files still hold. The principal discrepancies are underprediction of spectra in the low MeV range and substantial overprediction of spectra in the 50-500 keV range. Reductions in the high energy inelastic effectiveness for ENDF/B-III did not have a substantial effect on the experiment-theory comparison because the changes were essentially all above 2 MeV where the inelastic cross section is small. The principal experiment-theory discrepancies were in the low MeV range, below where the cross-section changes were made.

Uranium spectra also were studied with the FTR-300 S data set (Hanford) and with Gulf Radiation Technology data, the latter data including the effects of the $(n,\gamma;n')$ reaction proposed at GRT to resolve low-energy discrepancies. The FTR-300 S data yielded experiment-theory comparisons similar to the various ENDF/B results. The GRT data, led to much worse overpredictions at low energies as a result of the $(n,\gamma;n')$ reaction.

Effort has proceeded on the continuous slowing down integral transport technique for space-dependent spectra. The technique has been applied to single-region depleted-uranium and iron problems and to two-region depleted-uranium-iron problems. Results in general have been quite good. The principal source of difficulty in problems considered to date has been streaming at deep-cross-section minima. Difficulties are reduced if the physical system is made larger, thereby reducing leakage. The difficulty

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*Based in part on the Ph.D. theses of M. Danchak, G. Epstein and S. Kang.

probably could be alleviated by more sophisticated leakage-absorption treatment in the reference case used for generating slowing down parameters.

The formulation of the technique was oriented to preserving the traditional slowing down relations as extended to matrix form. This approach aided in testing, since one could infer what appropriate orders of values of various matrix elements should be. However, the approach had the disadvantage of invoking more operations per lethargy interval than are actually necessary.

Analytical effort to facilitate applications of the interactive graphics system to interpretation of spectrum measurements has proceeded in parallel with graphics system development. Particular emphasis has been placed on reducing storage requirements to fall within time-sharing constraints. Substantial progress has been made in streamlining the calculations of the slowing down parameter and the age in generalized continuous slowing down theory.

The time-dependent slowing down study has been extended to include fertile materials. These materials can have fissions above a threshold energy. The analytical solution in terms of exponentials in each group has to be modified to a matrix problem above the threshold followed by individual group problems. The threshold in materials of interest (principally ^{238}U) is such that the matrix inversion is feasible. Test problems have been performed successfully.

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INSTRUMENTATION DEVELOPMENT

RENSSELAER INTERACTIVE GRAPHICS ANALYSIS SYSTEM

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

Throughout the relatively short period nuclear science has been a discipline, it has constantly been confronted with problems whose solutions lie close to the technological frontier. Experimental as well as theoretical techniques have depended heavily on the unique application of state-of-the-art electronics which have not merely aided the nuclear scientist and engineer, but made his field possible. High speed data acquisition has allowed measurement of nuclear parameters to the required accuracy. Mammoth calculating machines are a necessity for the development and subsequent production solutions of the various mathematical models. The results of these computer applications has led to an overwhelming amount of data which must yet be evaluated. Hence, one working in this field is forced to be highly proficient, not only in the increasingly complex nuclear areas, but in the computer field as well. This situation is rapidly overtaxing the capabilities of the individual and requires yet another application of the electronic computer.

The problem presented demands a two-fold solution. The evaluation of large amounts of data is feasible using one of the oldest methods, graphical representation, coupled with one of the newest, on-line computing, to spawn the technique of interactive graphics. However, given the basic ability to evaluate data via computer is not the end; one is still faced with the prodigious task of implementing this technique. The solution, then, must be a system which allows for the evaluation of large quantitites of data but which puts minimum demands on the evaluators. It is to this end that the Rensselaer Interactive Graphics Analysis System (RIGAS) addresses itself.

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

Design Criteria for RIGAS

The sole objective of this system is to provide a general analysis tool to facilitate the handling, evaluation and manipulation of large quantities of data by the prime user: scientists and engineers intimately familiar with that data. Since these users are to be the terminal operators, the system must have a high information bandwidth with a very short time required for proficiency. To accomplish this seemingly contradictory task, the following man-machine categories of dialogue have been specified:

1) Limited English Input

   Advantages: The user employs words he is familiar with.
   Disadvantages: Some users tend to overestimate the intelligence of the machine and overstep the tight restrictions on input wording.

2) Computer-Initiated Dialogues

   Advantages: The computer tells the operator what to do; little training is required. This dialogue can be used with a totally untrained operator.
   Disadvantages: Dialogue can be lengthy and often slow. Many characters required, hence, a high line utilization. More expensive networks are needed. Little flexibility is allowed in the sequence of operation.

3) Dialogues with a Light-Pen for Input

   Advantages: Simple form of input, ideal for an untrained operator. Can make a complex dialogue fast.
   Disadvantages: Limited in scope unless a keyboard is used as well.

4) Graphics using Chart Displays

   Advantages: Very effective for summarizing information and manipulating models. Ideal for many dialogues with management.
   Disadvantages: Expensive. Elaborate programming requirements. On teleprocessing systems "intelligent" terminals are needed to avoid information bandwidth restraints.

5) Graphics using Symbol Manipulation

Advantages: Very effective for complex problem solving, engineering design, etc.
Disadvantages: Expensive. Elaborate programming requirements. "Intelligent" terminals needed.

Judicious use of these five categories will effectively minimize the disadvantages of each. One further criteria must be specified. Since this is to be an "on-line" system, response times must be such as to not degrade the human capacity for thinking. Hence, response times shall, on the average, be no greater than 2 seconds. However, allowance will be made for longer times required for more complicated tasks providing adherence to psychological "closure" has been made.

With these system criteria in mind, one must select a graphics terminal utilizing keyboard, light-pen, pushbuttons and stylus for input and typewriter, graphics screen, light panel and facsimile machine for output. It was determined that the PDP-15 computer with 32K of core, 1 disk drive, 4 tape drives and an interactive graphics unit would suffice. These, however, must be augmented with additional pushbuttons, a light panel and a hard copy unit. Response time requirements, then, should provide no problem for locally generated displays. The addition of a 4800 baud maximum rate asynchronous data communications link for time-sharing and a 2000 baud synchronous link for batch operation to a remote machine, e.g., CDC-6600, will satisfy terminal requirements for processing not feasible locally. Although the use of a remote computer may degrade response times, processing in this mode would qualify as a complicated task and can be made tolerable with the proper psychological considerations, such as the use of interim responses.

The actual dialogue structure between individual users will vary greatly. However, there are points of commonality and it is upon these that the system is based. The first, and most obvious, is the entry of raw data, that is, the data to be evaluated or manipulated. Once this is accomplished, the user is presented with five functions which may be selected in any order and at any frequency. These are:

1) the display of textual information that is part of the entered data.
2) the selection of the whole or parts of the data entered for display.
3) the display of that selected data.
4) the ability to change scale and manipulate that data.
5) the ability to call user or library subroutines which act on the displayed data.

It is believed that these functions will satisfy most user requirements and still be incorporated into the same system.

Accomplishments to Date

Implementation of RIGAS falls into two basic categories — hardware and software. All major items of hardware have been procured or constructed with the exception of the synchronous communications link. This has been designed and is currently being built. Software programming has advanced to include the first four functions listed above as well as data entry. Once provisions for calling special subroutines to act on displayed data are incorporated, the system will be bullet-proofed and fine tuned before use with a demonstration problem. This problem will be the assessment and modification of neutron cross sections using slowing down theory. Given a multigroup cross section set, the slowing down parameters and Fermi age will be computed. The latter will be iteratively adjusted via light-pen to produce fluxes in agreement with experimental results using the "on-line" remote computer. This resulting Fermi age will then be used to assess current multigroup cross sections sets and reflect modifications necessary.

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*October 1, 1972 - September 30, 1973

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