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LINEAR ACCELERATOR PROJECT

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

PROGRESS REPORT

for

October 1, 1972 - December 31, 1972

Rensselaer Polytechnic Institute
Troy, New York 12181

Erwin R. Gaerttner
Project Director

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NEUTRON CROSS SECTIONS

FISSION NEUTRON MULTIPLICITY MEASUREMENTS ON ^{239}Pu

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

Nubar measurements were made on ^{239}Pu using a 1.4 gram multiplate fission chamber¹ and an improved detector system.² The primary measurements were made in the resonance region from 7 to 100 eV. A separate series of runs were made over the thermal region and up to the 0.3 eV resonance.

Nubar values have been obtained for about 22 resonances with standard deviations from 0.2 to 0.5%. The spread in nubar values for the resonances is larger than their error bars. Statistical tests indicate that the distribution in nubar values corresponds to two or more populations.

Comparisons have been made to previous results.^{3,4} Our latest data are in agreement in shape with Weinstein³ if we propose that Weinstein's data above about 45 eV are re-normalized downward slightly. (This normalization problem did not occur in the present results since the new data acquisition system enabled us to cover the 7 to 100 eV region in one measurement.) If an arbitrary normalization is made, our latest nubar results and those of Weston⁴ also look similar in shape. There is a tendency for our values to lie below Weston's for energies less than 20 eV and above his for energies greater than 60 eV. Both sets of data show a pronounced dip in nubar in the 42 and 45 eV resonances. When the thermal nubar data are processed, the resonance data will be normalized to the thermal value and absolute nubar comparisons can be made.

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1. Borrowed from Oak Ridge National Laboratory.
2. Linear Accelerator Project Annual Technical Report, October 1, 1971 - September 30, 1972, 41, COO-3058-27 and Ph.D. Thesis of R. L. Reed.
3. S. W. Weinstein, R. L. Reed and R. C. Block, Physics and Chemistry of Fission, I.A.E.A. II, 447 (1969).
4. L. W. Weston and J. Todd, Conf. Neutron Cross Sections and Technology, University of Tennessee 2, 861 (1971).

FISSION MULTIPLICITY MEASUREMENTS ON ^{233}U AND ^{235}U

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

We have used the liquid scintillator method to measure relative $\bar{\nu}$ (nubar) values over the thermal and resonance energy regions of ^{233}U and ^{235}U . Resonances were resolved up to 30 eV for ^{235}U and 100 eV for ^{233}U .

Figure 1 is a sketch of the general system used. Neutrons from the LINAC neutron target assembly are allowed into an evacuated 25-meter flight path where they are collimated to produce a 3-in.-diameter beam on the fission chamber. The fission chamber is placed in the center of the gadolinium-loaded liquid scintillator tank. The incident neutrons cause fission in the fissile material (^{233}U , ^{235}U) of the chamber. Ionization caused by a fission fragment results in a "fission chamber pulse." At the same time the scintillator tank responds to prompt gamma radiation emitted from the fissioning nucleus and produces a "tank fission pulse." These two pulses are required to be in coincidence for a fission event. This coincidence requirement serves to eliminate alpha pileup events in the fission chambers being taken for fissions. There are some accidental coincidences between tank backgrounds and alpha pulses, but corrections are made in the analysis. Typical correction factors are $\sim 0.001\%$ (negligible) for ^{235}U and $\sim 0.1\%$ for ^{233}U with a coincidence resolving time of 119 nanoseconds. The detection efficiency of the coincidence system is better than 70% in relation to the fissions detected by the fission chamber alone. (This figure is based on data from a small source ^{252}Cf chamber with a fission rate of $\sim 6/\text{sec.}$).

Most of the prompt fission neutrons emitted from the fissioning nucleus enter the scintillator tank where they are thermalized in about 1 μsec by hydrogen scattering in the scintillant.

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

These neutrons are then captured in the gadolinium and hydrogen (~4% are captured in hydrogen) with a mean lifetime of ~10 microseconds. About 90% of the emitted neutrons are captured in the scintillator tank. Starting one microsecond after a fission event takes place, the neutron capture events in the tank are counted for 32 microseconds. This neutron count is then sent to the PDP-7 computer along with time-of-flight information for the incident neutron energy. The control of the timing sequences is in the "Nubar Logic Unit." This logic unit also requires that detected fissions be separated by at least 128 microseconds; if they are not, the corresponding neutron counts and time-of-flight information are not transferred to the computer.

Not all of the events counted in the tank are due to fission neutrons from the detected fission events. Some sources of background in the scintillator tank are listed below:

1. Neutrons from undetected fissions.
2. Neutrons scattered into the tank by chamber materials (aluminum and uranium).
3. Neutron capture in chamber materials.
4. Gamma radiation from undetected fissions.
5. Natural background, e.g., cosmic radiation, etc.
6. Delayed neutrons.
7. Activities of some fissile samples.

To measure the background contribution, the background is sampled in an asynchronous manner. A background sampling generator sends a random pulse to the logic unit. If no fission has taken place, a neutron count is initiated. This count and its corresponding time-of-flight information are sent to the PDP-7 as a background count. Background counts are accepted only if separated from a fission event by more than 128 microseconds.

As is seen in Fig. 1, a ^{252}Cf fission chamber is placed in the through tube of the scintillator tank along with the uranium fission chamber, but out of the neutron beam. Data are taken for ^{252}Cf in time-of-flight along with the uranium data. Changes in

detector efficiency are corrected for by normalizing the uranium results for each data run to the ^{252}Cf detected nubar value.

More detail about the experimental setup can be found in Fig. 2.

Five different sets of data were taken in the ^{233}U and ^{235}U measurements. Table 1 lists the samples, time-of-flight start delay for the RPI time-of-flight clock, the energy region covered, linac repetition rate and electron beam burst width and the amount of machine time used for each data set. The data were accumulated in runs of $\frac{1}{2}$ to 4 hours duration. Most of the ^{233}U data were in runs of $\frac{1}{2}$ to 2 hours duration. This was done to ensure that only small amounts of data would be lost due to breakdowns or other possible problems in the linac and detector system. Each of these short runs can be analyzed and checked. Suspect data runs can be deleted from the final analysis.

The data are acquired by a PDP-7 computer which stores 10440 pieces of primary data in 6090 memory locations using a special split-word-storage data acquisition program. Other memory locations are used for run information, which bring the total data region to 6144 memory core locations. The data are stored as a function of three variables: the event type (regular fission, ^{252}Cf fission, or background), the time-of-flight of the event, and the neutron multiplicity detected for the event (stored multiplicities are from 0 to 11). The 6090 core locations are thus divided into 3 event type regions. Each region contains 7 multiplicity blocks, and each block consists of 290 time-of-flight channels. Blocks 1 to 4 are used to store multiplicities of 0 to 3 and blocks 5 to 7 are used in split-word configurations to store multiplicities 4 to 11. A variable time-compression point and a variable time compression factor are used in the time-of-flight areas.

Nubar values are calculated for each time-of-flight channel with corrections made for accidental coincidences due to alpha-pulse pileup, background in the neutron detector, and neutron deadtime counting losses. Figures 3 and 4 present efficiency-

corrected nubar values as a function of time-of-flight channel for each data set. The vertical portion of each data point indicates the associated statistical error.

The nubar value for a resonance is determined as a weighted average of the channel-by-channel nubar values over the time-of-flight region corresponding to the resonance. The weighting factor is the inverse of the square of the statistical (counting) error. Each averaging region is chosen so as to have each resonance isolated where possible. In those cases where resonances interfere or are too close to be completely isolated, only the central portions or those portions not affected, or only slightly affected, by neighboring resonances are selected. The averaging regions in the thermal energy region are chosen to have approximately equal statistical errors. The averaging regions for each data set are presented in Figs. 5 and 6. Each plot is of the detected fissions per channel for each data set with the averaging regions indicated by the shaded areas. The particular data set is indicated by the title above each plot. The number above each shaded region is used in the tables of nubar values (Tables 2 to 6) as a region indicator.

The region-averaged nubar values are presented in Figs. 7 to 11 and Tables 2 to 6 for each data set. In the Figures, each plotted point represents the nubar value and its associated statistical error. The error is indicated by the vertical portion of the plotted point and the time-of-flight averaging region in channels is indicated by the central horizontal line. The incident neutron energy for the region (peak energy for a resonance and average energy for a thermal region) is given above each plotted point in electron volts. In the Tables, each nubar value is accompanied by the following nine columns:

1. Region number -- indicated above each shaded region in the corresponding plot of Figs. 5 and 6.

2. NF and
3. NL -- the first and last time-of-flight channels of the averaging region.
4. Region type -- "Res" indicates a resonance; "Res*" indicates a resonance whose averaging region assignment may include too much effect from nearby resonances; and "Thermal" indicates a thermal region point. Doublets or triplets are indicated by "Doublet" and "Triplet."
5. Energy of the resonance or thermal region in electron volts.
6. Nubar value.
7. Statistical error on the reported nubar value.
8. Deadtime correction -- correction calculated to account for neutron-counting dead-time losses.
9. Accidental Coincidence Correction -- correction for accidental coincidences in fission detection due to alpha-pulse pileup from the fission chambers. Shown only for ^{233}U . (below 1.0001 for most of the ^{235}U values).

Table 7 summarizes some variations observed in each of the data sets. The error range values give the maximum and minimum observed statistical errors for each of the data sets in percent of the detected nubar value. The "maximum deviation from the average" values gives the largest observed difference between any nubar value of the set and the average of the entire set in percent of the average. Under the heading "maximum region-to-region difference" is shown the largest difference between any two nubar values in the data set. This Table thus gives the statistical quality of each data set in terms of the errors and observed deviations between nubar values in that data set.

Statistical tests have shown that the deviations from an average observed in the resonance region data are not consistent with a normal (Gaussian) distribution. This is most apparent for

the ^{235}U resonance region data where the nubar values appear to be separated into at least two groups. These two groups have a separation of about 0.5%. Chi-square tests show a better than 75% probability that two (or more) Gaussian distributions will fit the observed results while a single Gaussian has only a 5% probability of fitting the observations.

Possible correlations of the observed nubar values with reported resonance parameters, such as fission and radiation widths, were tested, but no significant correlations were found. However, the high-low nature of the observed grouping coincides with some resonance spin assignments similar to those reported by other investigators^{1,2,3,4}. Assuming that the 8.79 eV resonance is of spin 3^- and the 19.3 eV resonance is of spin 4^- , spin assignments based on the high-low groupings in ^{235}U were made and are shown in Table 8 with the nubar values and associated errors. Also included are assignments from several other investigations.⁴

Only the ^{235}U data showed sufficient group separation to allow resonance spin assignments by this method. The ^{233}U data exhibit variations of sufficient magnitude to imply more than one group of nubar values, but distinct groupings are not observed, and hence no spin assignments are made for ^{233}U .

REFERENCES:

1. Linear Accelerator Project Progress Report, January - March January - March 1969, RPI-328-160.
2. S. Weinstein, Ph.D. Thesis, RPI, 1969 (unpublished).
3. Linear Accelerator Project Annual Technical Report, October 1, 1968 - September 30, 1969, RPI-328-171.
4. S. Weinstein et al., Physics and Chemistry of Fission, I.A.E.A., II, 447 (1969).

FIGURE CAPTIONS

- Fig. 1 Major Components of the Nubar Experiment.
- Fig. 2 Block Schematic of the Nubar Experiment.
- Fig. 3 ^{235}U Nubar Values for Individual Time-of-Flight Channels
Upper: Resonance Region 5 to 30 eV
Lower: Thermal Region
- Fig. 4 ^{233}U Nubar Values for Individual Time-of-Flight Channels
Upper: Resonance Region 5 to 40 eV
Middle: Thermal Region
Lower: Resonance Region 20 to 100 eV
- Fig. 5 Selected Averaging Regions for ^{235}U Nubar Data
Upper: Thermal Region
Lower: Resonance Region 5 to 30 eV
- Fig. 6 Selected Averaging Regions for ^{233}U Nubar Data
Upper: Resonance Region 5 to 40 eV
Middle: Thermal Region
Lower: Resonance Region 20 to 100 eV
- Fig. 7 ^{235}U Resonance Region Averaged Nubar Values.
- Fig. 8 ^{235}U Thermal Region Averaged Nubar Values.
- Fig. 9 ^{233}U Resonance Region Averaged Nubar Values 5 to 40 eV.
- Fig. 10 ^{233}U Thermal Region Averaged Nubar Values.
- Fig. 11 ^{233}U Resonance Region Averaged Nubar Values 20 to 100 eV.

TABLE CAPTIONS

- Table 1 Linac Time and Conditions for the ^{233}U and ^{235}U Nubar Measurements.
- Table 2 ^{235}U Resonance Region (5 to 30 eV) Nubar Values.
- Table 3 ^{235}U Thermal Region (0 to 10 eV) Nubar Values.
- Table 4 ^{233}U Resonance Region (5 to 40 eV) Nubar Values.
- Table 5 ^{233}U Thermal Region (0 to 10 eV) Nubar Values.
- Table 6 ^{233}U Resonance Region (20 to 100 eV) Nubar Values.
- Table 7 Observations on Result of ^{235}U and ^{233}U Nubar Measurements.
- Table 8 ^{235}U Resonance Spin Assignments.

EVACUATED
FLIGHT PATH

CF-F.C.

DETECTOR
ELECTRONICS

FISSION

CF
ROUTING

NEUTRON
PULSES

BACKGROUND
SAMPLING
GENERATOR

NUBAR
LOGIC
UNIT

FISS CF 2³ 2² 2¹ 2⁰ STOP

PDP-7
COMPUTER

RPI
TIME
OF
FLIGHT
CLOCK

MAJOR COMPONENTS OF
NUBAR EXPERIMENT

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

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

<u>Sample</u>	<u>T-O-F Delay</u>	<u>Region (energies spanned)</u>	<u>Compression Point (channel widths in μsec)</u>	<u>Linac Time</u>	<u>Burst Width</u>	<u>Rep. Rate</u>	
^{235}U	349 μsec	Resonance (5 to 28 eV)	201 (1,4)	165 hours	0.25 μsec	300 pps	21
^{235}U	549 μsec	Thermal (0.008 to 10 eV)	151 (8,128)	60 hours	0.25 μsec	33 pps	
^{233}U	289 μsec	Resonance (5 to 40 eV)	181 (1,4)	200 hours	0.25 μsec	300 pps	
^{233}U	520 μsec	Resonance (0.008 to 10 eV)	151 (8,128)	72 hours	0.25 μsec	33 pps	
^{233}U	172 μsec	Resonance (20 to 100 eV)	101 ($\frac{1}{2}$,1)	40 hours	0.25 μsec	300 pps	

Table 2. ^{235}U Resonance Region (5 to 30 eV) Nubar Values

<u>Region</u>	<u>NF</u>	<u>NL</u>	<u>Region Type</u>	<u>Energy (eV)</u>	<u>Nubar</u>	<u>Error</u>	<u>Deadtime Correction**</u>
1	5	8	Res	26.48	2.421	.006	1.0068
2	12	16	Res	25.55	2.422	.005	1.0068
3	21	23	Res	24.32	2.419	.007	1.0068
4	26	29	Res*	23.65	2.417	.005	1.0068
5	33	35	Res	22.95	2.420	.007	1.0068
6	47	51	Res	21.10	2.414	.005	1.0068
7	64	71	Res	19.30	2.405	.004	1.0067
8	79	84	Res	18.05	2.407	.005	1.0066
9	97	101	Res	16.67	2.414	.006	1.0066
10	106	109	Res	16.10	2.404	.007	1.0066
11	115	120	Res	15.45	2.407	.006	1.0065
12	168	175	Res	12.39	2.407	.004	1.0065
13	185	190	Res	11.67	2.403	.006	1.0065
14	206	207	Res	10.16	2.395	.006	1.0064
15	212	213	Res	9.30	2.414	.005	1.0066
16	217	222	Res	8.79	2.414	.003	1.0065
17	233	237	Res	7.08	2.420	.005	1.0064
18	243	245	Res	6.39	2.417	.004	1.0063
19	269	273	Res	4.85	2.394	.007	1.0062

* May include tails of other resonances.

** Accidental coincidence correction is less than 1.0001 for all resonances.

Table 3. ^{235}U Thermal Region (0 to 10 eV) Nubar Values

<u>Region</u>	<u>NF</u>	<u>NL</u>	<u>Region Type</u>	<u>Energy (eV)</u>	<u>Nubar</u>	<u>Error</u>	<u>Deadtime Corrections *</u>
1	8	10	Res	8.79	2.419	.009	1.0063
2	16	18	Res	7.08	2.443	.020	1.0063
3	21	22	Res	6.39	2.418	.018	1.0062
4	35	35	Res	4.85	2.443	.050	1.0062
5	50	53	Res	3.61	2.449	.017	1.0062
6	59	62	Res	3.15	2.446	.019	1.0062
7	88	96	Res	2.04	2.387	.021	1.0061
8	140	151	Res	1.135	2.433	.008	1.0061
9	159	164	Res	0.290	2.433	.005	1.006
10	170	180	Thermal	0.141	2.422	.004	1.006
11	181	190	Thermal	0.087	2.428	.004	1.006
12	191	200	Thermal	0.059	2.425	.004	1.006
13	201	210	Thermal	0.043	2.429	.004	1.006
14	211	220	Thermal	0.033	2.426	.004	1.006
15	221	230	Thermal	0.026	2.428	.004	1.006
16	231	245	Thermal	0.020	2.429	.004	1.006
17	246	260	Thermal	0.015	2.427	.004	1.006
18	261	275	Thermal	0.012	2.426	.005	1.006

* Accidental coincidence correction is less than 1.0001. In all, except the 2.04 eV resonance region, the correction is less than 1.00003.

Table 4. ^{233}U Resonance Region (5 to 40 eV) Nubar Values

<u>Region</u>	<u>NF</u>	<u>NL</u>	<u>Region Type</u>	<u>Energy (eV)</u>	<u>Nubar</u>	<u>Error</u>	<u>Deadtime Correction</u>	<u>Accidental Coincidence Correction</u>
1	9	10	Res	38.0	2.515	.011	1.0078	1.0022
2	13	14	Res	37.1	2.486	.009	1.0078	1.0015
3	21	26	Res	34.9	2.511	.005	1.0078	1.0013
4	33	38	Res	32.3	2.511	.005	1.0077	1.0014
5	40	42	Res	31.2	2.532	.008	1.0077	1.0016
6	48	52	Res	29.2	2.502	.006	1.0076	1.0011
7	54	59	Res*	28.48	2.515	.007	1.0076	1.0026
8	63	67	Res	27.0	2.519	.007	1.0075	1.0020
9	73	76	Res	25.5	2.509	.006	1.0076	1.0012
10	84	88	Res	24.0	2.509	.006	1.0076	1.0015
11	94	100	Res	22.5	2.525	.004	1.0076	1.0004
12	102	106	Res	22.15	2.504	.005	1.0075	1.0006
13	112	117	Res	20.8	2.520	.005	1.0075	1.0011
14	128	133	Res	19.1	2.485	.004	1.0074	1.0005
15	136	138	Res*	18.6	2.487	.008	1.0074	1.0015
16	141	145	Res	18.1	2.485	.007	1.0074	1.0018
17	157	162	Res	16.7	2.519	.005	1.0074	1.0009
18	165	169	Res*	16.4	2.522	.005	1.0074	1.0008
19	175	180	Res	15.5	2.509	.005	1.0073	1.0007
20	186	187	Res	13.8	2.502	.006	1.0073	1.0014
21	190	194	Res	12.9	2.501	.003	1.0073	1.0007

* May include tails of other resonances.

Table 4. (continued)

<u>Region</u>	<u>NF</u>	<u>NL</u>	<u>Region Type</u>	<u>Energy (eV)</u>	<u>Nubar</u>	<u>Error</u>	<u>Deadtime Correction</u>	<u>Accidental Coincidence Correction</u>
22	199	200	Res	11.5	2.506	.006	1.0073	1.0015
23	202	209	Res	10.4	2.508	.003	1.0073	1.0006
24	213	214	Res	9.3	2.491	.006	1.0071	1.0018
25	218	221	Res	8.75	2.501	.006	1.0071	1.0034
26	230	231	Res	7.6	2.505	.008	1.0071	1.0027
27	235	245	Res	6.82	2.493	.003	1.0071	1.0006
28	250	254	Res	5.95	2.497	.004	1.0071	1.0013
29	265	283	Res	4.81	2.475	.003	1.0069	1.0016

Table 5. ^{233}U Thermal Region (0 to 10 ev) Nubar Values

<u>Region</u>	<u>NF</u>	<u>NL</u>	<u>Region Type</u>	<u>Energy (eV)</u>	<u>Nubar</u>	<u>Error</u>	<u>Deadtime Correction</u>	<u>Accidental Coincidence Correction</u>
1	5	6	Res	10.45	2.501	0.010	1.0074	1.0003
2	9	10	Res	9.30	2.506	0.023	1.0073	1.0014
3	21	25	Res	6.82	2.498	0.008	1.0073	1.0004
4	28	31	Res	5.95	2.482	0.015	1.0072	1.0010
5	33	46	Res	4.81	2.477	0.010	1.0072	1.0013
6	51	58	Res	3.66	2.487	0.010	1.0071	1.0009
7	82	90	Res	2.30	2.475	0.007	1.0071	1.0004
8	98	128	Doublet	1.68	2.502	0.004	1.0070	1.0003
9	168	177	Thermal	0.164	2.5015	0.0040	1.0069	1.0012
10	178	185	Thermal	0.104	2.4986	0.0038	1.0069	1.0009
11	186	198	Thermal	0.068	2.4987	0.0032	1.0069	1.0007
12	199	209	Thermal	0.046	2.5064	0.0035	1.0069	1.0008
13	210	222	Thermal	0.033	2.5008	0.0036	1.0069	1.0009
14	223	238	Thermal	0.023	2.5051	0.0038	1.0068	1.0013
15	239	261	Thermal	0.016	2.5018	0.0041	1.0068	1.0021
16	262	290	Thermal	0.010	2.5019	0.0050	1.0068	1.0041

Table 6. ^{233}U Resonance Region (20 to 100 eV) Nubar Values

<u>Region</u>	<u>NF</u>	<u>NL</u>	<u>Region Type</u>	<u>Energy (eV)</u>	<u>Nubar</u>	<u>Error</u>	<u>Deadtime Correction</u>	<u>Accidental Coincidence Correction</u>
1	2	6	Doublet	111.53	2.523	.017	1.0089	1.0012
2	8	11	Res	108.1	2.492	.017	1.0088	1.0011
3	16	17	Res	103.9	2.441	.040	1.0086	1.0034
4	21	22	Res	101.12	2.456	.030	1.0086	1.0020
5	24	26	Res	98.7	2.504	.019	1.0087	1.0010
6	33	36	Res*	94.6	2.487	.025	1.0086	1.0025
7	39	41	Res	91.2	2.527	.020	1.0087	1.0011
8	44	52	Triplet	86.2	2.548	.028	1.0087	1.0069
9	57	61	Res	83.2	2.531	.019	1.0086	1.0016
10	64	70	Doublet	80.4	2.494	.017	1.0085	1.0016
11	76	78	Res*	75.9	2.510	.019	1.0085	1.0008
12	80	83	Res*	74.4	2.510	.016	1.0085	1.0008
13	91	97	Res*	70.7	2.483	.017	1.0084	1.0018
14	104	107	Res	64.8	2.511	.017	1.0084	1.0019
15	109	113	Doublet	61.5	2.509	.015	1.0084	1.0018
16	117	130	Triplet	56.6	2.498	.009	1.0083	1.0012
17	139	141	Res	49.1	2.503	.017	1.0082	1.0012
18	144	148	Doublet	47.6	2.497	.019	1.0081	1.0028
19	158	168	Res	43.2	2.497	.022	1.0081	1.0021
20	164	171	Doublet	40.6	2.516	.014	1.0081	1.0019
21	176	178	Res	38.1	2.455	.021	1.0079	1.0021

*May include tails of other resonances.

Table 6. (continued)

<u>Region</u>	<u>NF</u>	<u>NL</u>	<u>Region Type</u>	<u>Energy (eV)</u>	<u>Nubar</u>	<u>Error</u>	<u>Deadtime Correction</u>	<u>Accidental Coincidence Correction</u>
22	180	182	Res	37.10	2.522	.019	1.0081	1.0014
23	188	197	Res	34.9	2.514	.011	1.0080	1.0011
24	201	204	Res	32.3	2.505	.014	1.0079	1.0009
25	208	210	Res	31.2	2.543	.018	1.0080	1.0013
26	215	220	Res	29.2	2.516	.012	1.0078	1.0009
27	232	234	Res	27.0	2.517	.019	1.0078	1.0014
28	239	244	Res	25.5	2.511	.013	1.0078	1.0011
29	251	255	Res	24.0	2.539	.015	1.0079	1.0011
30	259	267	Res	22.5	2.533	.009	1.0078	1.0004
31	269	272	Res	22.15	2.527	.011	1.0078	1.0004
32	278	287	Res	20.8	2.530	.011	1.0078	1.0011

Table 7. Observations on Result of ^{235}U and ^{233}U Nubar Experiment^a

<u>Sample</u>	<u>Region</u>	<u>Error Range (Standard Deviation)</u>	<u>Maximum Deviation from Average^b</u>	<u>Maximum Region-to- Region Difference</u>
^{235}U	Resonance (5 to 30 eV)	0.1% to 0.3%	0.7%	1%
^{235}U	Thermal (0 to 10 eV)	0.15% to 0.2%	0.2%	0.3%
^{233}U	Resonance (5 to 40 eV)	0.12% to 0.5%	1%(0.75%) ^c	2%(1.5%) ^c
^{233}U	Thermal (0 to 10 eV)	0.12% to 0.2%	0.2%	0.3%
^{233}U	Resonance (20 to 100 eV)	0.35% to 1.6%	3%	4%

^aFor the thermal data sets, the quoted errors and relative differences refer only to the thermal region below 0.2 eV.

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

^cThe values in parentheses are acceptable if the two points with greatest deviation are dropped.

Table 8. ^{235}U Resonance Spin Assignments

Spin Assignments**

Resonance Energy (eV)	Nubar	This Work	Previous RPI Work (Ref. 4)	Asghar et al ⁺	Weigmann ⁺
26.48	2.421 $\pm$ 0.006	3			
25.55	2.422 $\pm$ 0.005	3			
24.32	2.419 $\pm$ 0.007	3			
23.65	2.417 $\pm$ 0.005	3			4
22.95	2.420 $\pm$ 0.007	3	3	3	3
21.10	2.414 $\pm$ 0.005	3	3		3
19.3	2.405 $\pm$ 0.004	4	4	4	
18.05	2.407 $\pm$ 0.005	4	4	3	4
16.67	2.414 $\pm$ 0.006	(3)	4	3	3
16.10	2.404 $\pm$ 0.007	4	4	U	3
15.45	2.407 $\pm$ 0.006	4	U*	3	3
12.39	2.407 $\pm$ 0.004	4	4	4	4
11.67	2.403 $\pm$ 0.006	4	4	4	
10.16	2.395 $\pm$ 0.006	4			
9.30	2.414 $\pm$ 0.005	(4)			
8.79	2.414 $\pm$ 0.003	3	3	3	
7.08	2.420 $\pm$ 0.005	3	3	3	3
6.39	2.417 $\pm$ 0.004	3	4	4	4
4.85	2.394 $\pm$ 0.007	4			
1.135	2.433 $\pm$ 0.008	3			
0.290	2.433 $\pm$ 0.005	3			

* Unassigned

** Parentheses indicate uncertain assignment

+ As quoted in Reference 4

AVERAGE CAPTURE CROSS SECTION OF DEPLETED URANIUM
IN THE ENERGY RANGE 10 KEV - 100 KEV⁺

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

The ~~average capture cross section of depleted uranium~~ (99.8% ²³⁸U and 0.2% ²³⁵U) has been extracted from the average transmission data, <TR>, and the average self-indication ratio data, <SIR>, in the energy range from 10 to 100 keV. The details of the experiments and of the calculational method have been described in previous reports.^{1,2,3}

Fits to the data have been attempted in two ways; one is by using the local average resonance parameters for each 10%-wide energy bin¹, and the other is by using the grand average resonance parameters over the full energy range.

The results are shown in Figs. 1, 2 and 3. The comparison of our results with others (ENDF/B-III by Pitterle and Durston, and James in England) shows that the average self-indication ratios calculated by using both the resonance parameters of ENDF/B-III and of James consistently predict higher values than the experimental data as can be seen in Fig. 2. Good agreement was obtained in the average transmission (Fig. 3).

The average resonance parameters as well as their goodness of fit are shown in Table 1. Our best-fit average resonance parameters give a p-wave level spacing and radiative capture width almost twice as large as ENDF/B-III and James, while keeping the p-wave capture strength function the same.

The average capture cross sections determined from both the global fit and local fit are shown and compared with other calculations in Fig. 1. Our results are in essential agreement with other calculations.

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^{*}Based in part on the Ph.D. Thesis of T. Y. Byoun.

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REFERENCES:

1. T. Y. Byoun, R. C. Block and T. Semler, Conf.-720901, ANS Topical Meeting on New Development in Reactor Physics and Shielding (September 1972).
2. Linear Accelerator Project Annual Technical Report, October 1, 1971 - September 30, 1972, COO-3058-27.
3. Linear Accelerator Project Progress Report, April - June 1972, COO-3058-21.

FIGURE CAPTIONS

- Fig. 1 Average Capture Cross Sections in the Energy Range 10 - 100 keV.
- Fig. 2 Average Transmission Compared with Calculations.
- Fig. 3 Average Self-indication Ratio Compared with Calculations.

Figure 1

Figure 2

Figure 3

Table 1. Comparison of the Average Resonance Parameters and Goodness of Fit

		R.P.I.	Pitterle and Durstun (ENDF/B-III)	James
Strength Functions (a)	S_0	1.0	1.05	0.93
S_ℓ (10^{-4})	S_1	1.48	1.75	1.58
Level Spacing	$\bar{D}_0$	20.5	20.0	22.5
D_ℓ (eV)	$\bar{D}_1$	13.5	6.67	7.5
Radiation Width	$\Gamma_{\gamma 0}$	0.023	0.0235	0.023
$\Gamma_{\gamma \ell}$ (eV)	$\Gamma_{\gamma 1}$	0.050	0.0235	0.023
$\overline{\Delta R}_{\langle TR \rangle}$ (b)		+0.03	+1.37	+0.27
$\overline{\Delta R}_{\langle SIR \rangle}$ (b)		-0.70	-1.39	-1.69

(a) Nuclear Radius, $R = 0.93 \times 10^{-12}$ cm was used

(b) The goodness of fit was calculated as following

$$\overline{\Delta R} = \sum_{i=30 \text{ keV}}^{100 \text{ keV}} (R_i^{\text{exp}} - R_i^{\text{cal}}) \times \frac{1}{\delta_{\text{Rexp}}} \frac{1}{N}$$

, where δ_{Rexp} = counting statistics of the experimental data

N = total number of data sets (for different energies, sample thicknesses, sample temperatures)

REACTOR PHYSICS AND ENGINEERING - EXPERIMENTAL

PERFORMANCE OF THE NEW TARGET FOR FAST SPECTRUM MEASUREMENTS

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

The new oil-cooled target¹ for fast and intermediate neutron spectrum studies, has been tested and is now being used routinely in measurements on the sodium assembly. It has performed satisfactorily over sustained periods of time. The power-handling capability of the target has attained its design objective of 5000 watts linac beam power, by increasing the rate of oil coolant flow. When used with the sodium assembly, the input power is limited by the radiological safety problem arising from the induced activity in sodium (the $^{27}\text{Al} (n,\alpha) ^{24}\text{Na}$ reaction with a half-life of 14.9 hours) and it is planned to operate the target at power levels not exceeding 3000 watts. At 3-KW electron beam power, the activity of the sodium assembly approaches about 5R per hour at the surface.

REFERENCE:

1. Linear Accelerator Project Annual Technical Report,
October 1, 1971 - September 30, 1972, 89, COO-3058-27.

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

PRELIMINARY COMPARISON OF MEASURED AND CALCULATED
FAST NEUTRON SPECTRA IN SODIUM

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

Preliminary calculations of the neutron spectra in the sodium assembly have been performed using the one-dimensional S_N transport code, DTF-IV,¹ with cross sections from ENDF/B-I.² These calculations are compared with the experimental data corrected for mean-emission times,³ deadtime losses, background, efficiency and absorption in the flight path. Figure 1 shows one such comparison for the 90° flux at two different radial positions ($R = 10.5$ in. and $R = 18.5$ in.). These calculations (P_{15} quadrature, P_8 scattering) were based on a 49-group cross-section set extending down to 10 keV.

The overall agreement in the spectrum shapes (no consideration was given to the amplitudes in these preliminary results) appears to be fair, although there are serious discrepancies in several parts of the spectra, particularly above 4 MeV. Part of the discrepancy may be due to the fact that source neutrons above 10 MeV have been excluded from the calculation. However, inclusion of source neutrons in the range from 10-15 MeV is expected to increase the calculated neutron flux in the highest neutron energy groups by only about 10 percent -- far short of the observed discrepancy.

Further measurements, as well as more refined calculations, are planned to be carried out.

The measurements will cover several more positions in the assembly. The calculations will involve ENDF/B Versions II and III and extension of multigroup data down to 100 eV. Extensive auxiliary calculations are necessary for pinpointing areas of inaccuracies in the cross-section data.

REFERENCES:

1. K. D. Lathrop, "DTF-IV — A Fortran IV Program for Solving the Multigroup Transport Equation with Anisotropic Scattering," LA-3373, Los Alamos Scientific Laboratory (1965).
2. Evaluated nuclear data file of the National Neutron Cross Section Center, Brookhaven National Laboratory (1967).
3. A. N. Mallen, N. N. Kaushal, B. K. Malaviya and E. R. Gaerttner, "Neutron Emission Time Effects in a Pulsed Sodium Assembly," Trans. Am. Nucl. Soc., 15, 899, 1972.

FIGURE CAPTION

Fig. 1 Preliminary Calculated (ENDF/B-I, P_{15} quadrature, 49-group, P_8 scattering) and Measured Fast Neutron Spectra in Sodium for $\theta = 90^\circ$, for (A) $R_A = 10.5$ in.; and (B) $R_B = 18.5$ in.

Figure 1

TRANSPORT CALCULATIONS OF FAST NEUTRON SPECTRA
USING DATA FILES FOR SODIUM

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

Preliminary calculations have been performed with the one-dimensional transport code DTF-IV, using data from ENDF/B file, Versions I, II and III. The range of the calculations has been extended down to 10 eV; scattering up to order P_3 has been included.

Mean-emission time corrections¹ can be applied to the time-of-flight data, based on calculations now covering the range 10 eV to 10 MeV. The effect of an angular dependent source term on the mean-emission time calculations is also being examined.

REFERENCE:

1. Linear Accelerator Project Annual Technical Report, October 1, 1971 - September 30, 1972, 109, COO-3058-27.

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

REACTOR PHYSICS AND ENGINEERING - THEORETICAL

ANALYSIS WITH ENDF/B-III AND OTHER DATA FILES

M. Becker

Forty-nine group ENDF/B-III P_8 data sets for ^{238}U , sodium, iron and aluminum were generated at Oak Ridge National Laboratory for us by R. Q. Wright using SUPERTOG (incorporating the RPI modifications for anisotropic weighting spectra). We modified the DLC-2 code to read these sets and generate DTF-IV input data. Analysis of spectra in ^{238}U has been performed. Calculations with the sodium data have been performed by A. Mallen of the experimental group.

Experiment-theory comparisons for ^{238}U indicate that difficulties we observed with earlier files still are present in ENDF/B-III. The flux in the 50-500 keV region still is over-predicted substantially, and the calculated flux still dips below the experiment in the low-MeV region. It thus appears that significant errors remain in both low and high energy inelastic data. It had been anticipated that hardening of the secondary inelastic distributions in ENDF/B-III would tend to reduce the high energy dip discrepancy. This has not proved to be the case. The reason probably is that the hardening was confined to the high MeV range, and did not have a substantial direct impact in the low MeV range where the discrepancy is. Table 1 lists in-group inelastic cross sections which illustrate this observation. If the secondary distribution is harder, and the total inelastic cross section unchanged (the case for the low MeV range), then the in-group cross section should be higher. This is not the case in the energy range where the discrepancy exists. Table 2 shows similar characteristics for one-group transfer.

We also have extended our analysis with Hanford data files to prediction of spectra in ^{238}U . Calculations were performed with the FTR-300S set. Again, the low energy flux was over-predicted. The FTR-300S set does not contain high-order aniso-

tropic data and has a substantially coarser group structure (sixteen groups rather than forty-nine between 10 keV and 10 MeV) than we usually use, so it is difficult to draw conclusions about high energy results.

We have acquired from Gulf Radiation Technology a data set for ^{238}U including the effect of the recently postulated $n, \gamma\text{-n}'$ reaction. We anticipate analysis of our experiment with these data in the near future.

Table 1. ^{238}U In-Group Inelastic Cross Section (barns)

<u>Group</u>	<u>Energy Range (MeV)</u>	<u>ENDF/B-II</u>	<u>ENDF/B-III</u>
1	8.82 - 10.0	3.56×10^{-6}	3.00×10^{-6}
2	7.79 - 8.82	1.10×10^{-5}	9.75×10^{-6}
3	6.87 - 7.79	3.83×10^{-5}	3.85×10^{-5}
4	5.35 - 6.87	5.93×10^{-4}	6.59×10^{-4}
5	4.72 - 5.35	4.42×10^{-4}	6.60×10^{-4}
6	4.17 - 4.72	7.34×10^{-4}	1.19×10^{-3}
7	3.68 - 4.17	1.19×10^{-3}	2.01×10^{-3}
8	3.25 - 3.68	1.84×10^{-3}	3.08×10^{-3}
9	2.87 - 3.25	3.62×10^{-3}	5.44×10^{-3}
10	2.23 - 2.87	7.55×10^{-2}	8.17×10^{-2}
11	1.97 - 2.23	.119	.117
12	1.74 - 1.97	.142	.138
13	1.53 - 1.74	.161	.160
14	1.35 - 1.53	.187	.187
15	1.19 - 1.35	.283	.283
16	1.05 - 1.19	.423	.423
17	.82 - 1.05	.893	.890

Table 2. ^{238}U Inelastic One-Group Downscatter

<u>Group Transfer</u>	<u>ENDF/B-II</u>	<u>ENDF/B-III</u>
1→ 2	2.45 x 10 ⁻⁵	2.06 x 10 ⁻⁵
2→ 3	6.99 x 10 ⁻⁵	6.17 x 10 ⁻⁵
3→ 4	8.94 x 10 ⁻⁴	8.82 x 10 ⁻⁴
4→ 5	1.56 x 10 ⁻³	1.88 x 10 ⁻³
5→ 6	2.12 x 10 ⁻³	3.01 x 10 ⁻³
6→ 7	3.32 x 10 ⁻³	5.07 x 10 ⁻³
7→ 8	5.07 x 10 ⁻³	8.05 x 10 ⁻³
8→ 9	7.50 x 10 ⁻³	1.17 x 10 ⁻²
9→10	3.36 x 10 ⁻²	4.86 x 10 ⁻²
10→11	4.10 x 10 ⁻²	5.34 x 10 ⁻²
11→12	8.16 x 10 ⁻²	7.52 x 10 ⁻²
12→13	.119	.109
13→14	.196	.193
14→15	.337	.337
15→16	.522	.512
16→17	.818	.797

CONTINUOUS SLOWING DOWN THEORY AND INTERFACES

G. Epstein* and M. Becker

Considerable progress has been made in checking out our continuous-slowing-down-integral-transport (CSDIT) interface treatment.¹ Numerical difficulties which had led to spurious amplitude discontinuities at interfaces have been identified and eliminated. Calculations have been performed on uranium-iron problems for which the CSDIT gives reasonable overall agreement with conventional multigroup transport calculations and provides for propagation of the fine structure of the iron region into the uranium. It is expected that some further refinements, principally to numerical technique and programming strategy, will be found desirable. However, the basic approach appears to be becoming useful.

REFERENCE:

1. Linear Accelerator Project Annual Technical Report, October 1, 1971 - September 30, 1972, 146, COO-3058-27.

*Based in part on the Ph.D. Thesis of G. Epstein.

INSTRUMENTATION DEVELOPMENT

RENSSELAER INTERACTIVE GRAPHICS ANALYSIS SYSTEM

M. Danchak,^{*} M. Becker and W. R. Moyer

Development of RIGAS (The Rensselaer Interactive Graphics Analysis System) has progressed to the point of hardware design to allow the analyzer to interact with the PDP-15 and CDC-6600 computers in the most effective and natural manner. A function switch system design has been completed to augment the capabilities of the PDP-15 and work is currently being done on interfaces between the two machines. Under development is a communications interface which will service both a standard teletype (110 baud) and a high speed data set (1200 baud).

Software design is concentrating on the reduction of required core for display of data as well as economic and efficient data handling techniques.

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